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BRITISH WELDING JOURNAL

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VOL. 8 NO. 5

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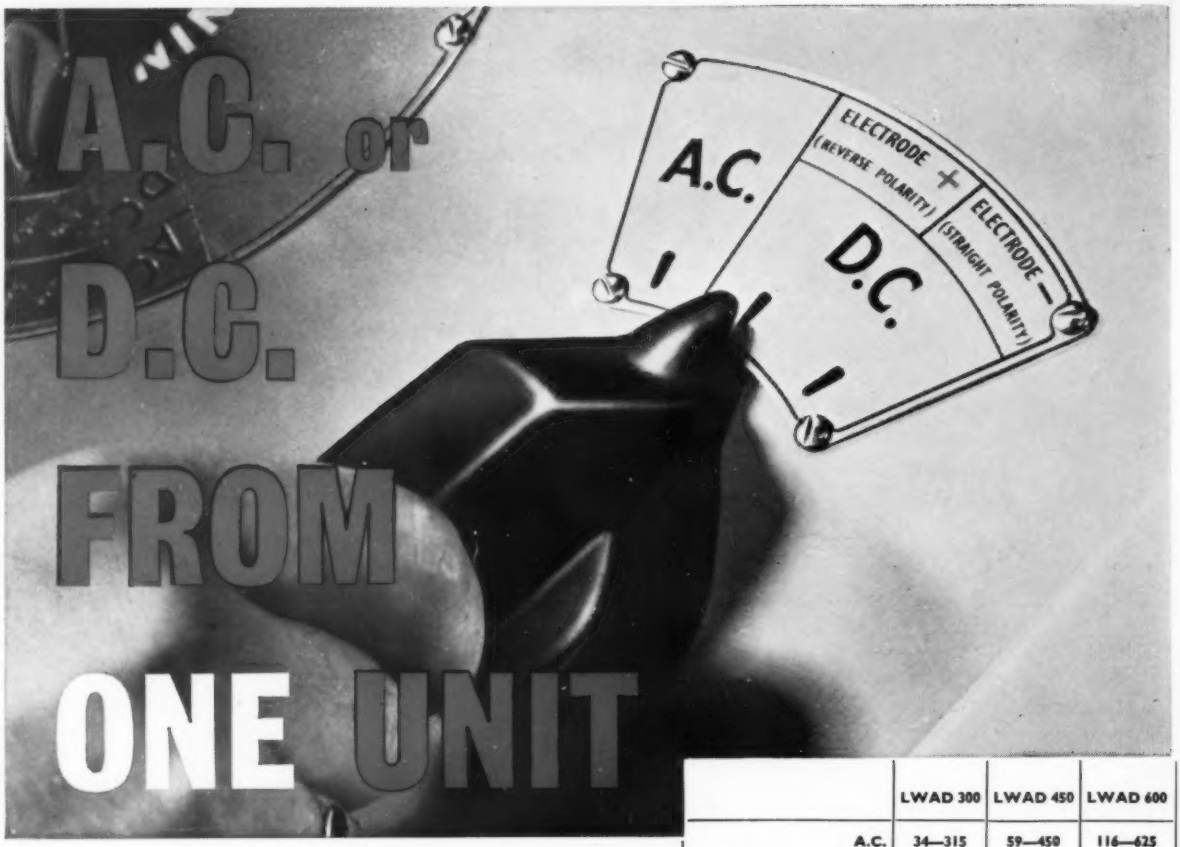
By A. A. Wells, M. S. Toms, P. Whitaker and C. F. Tipper

Cover Illustration

Welding 6 in. thick pure aluminium



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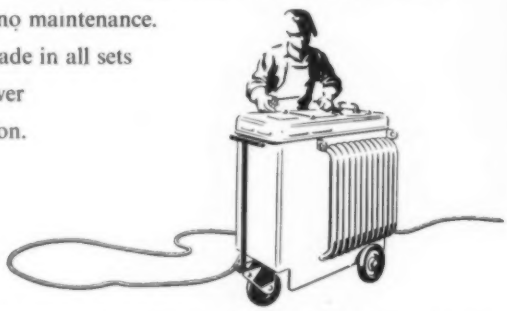

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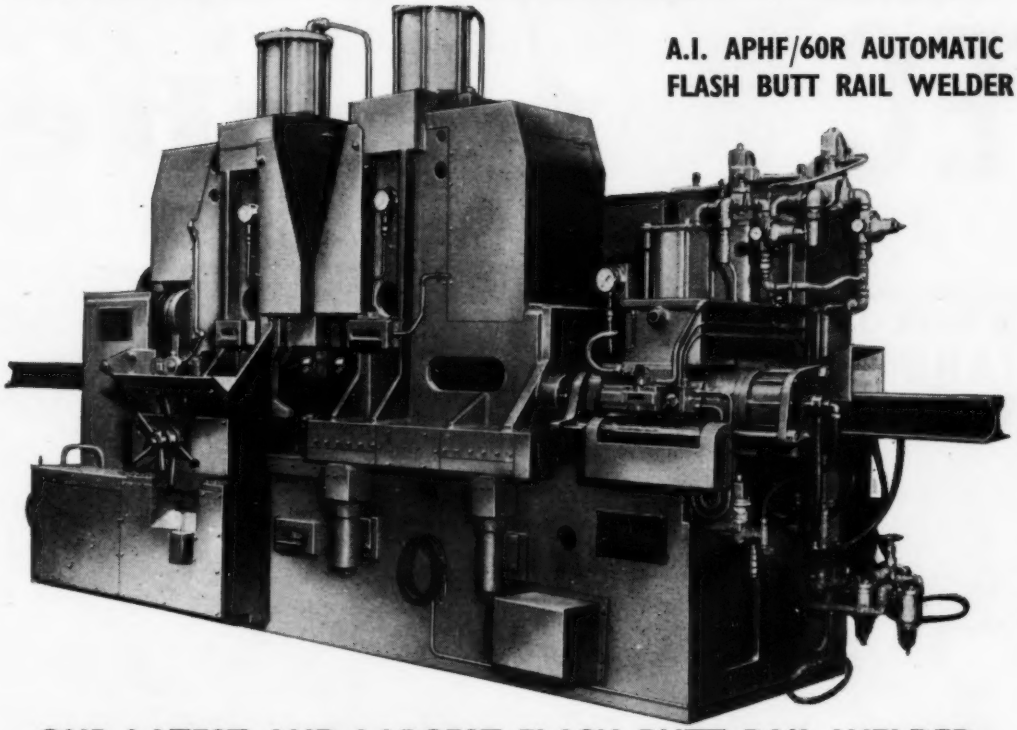

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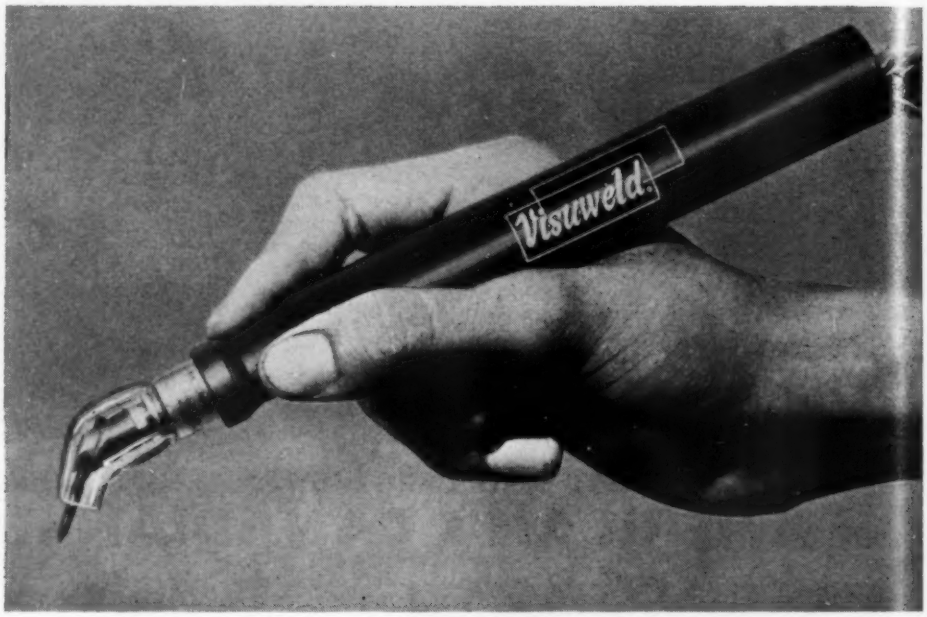

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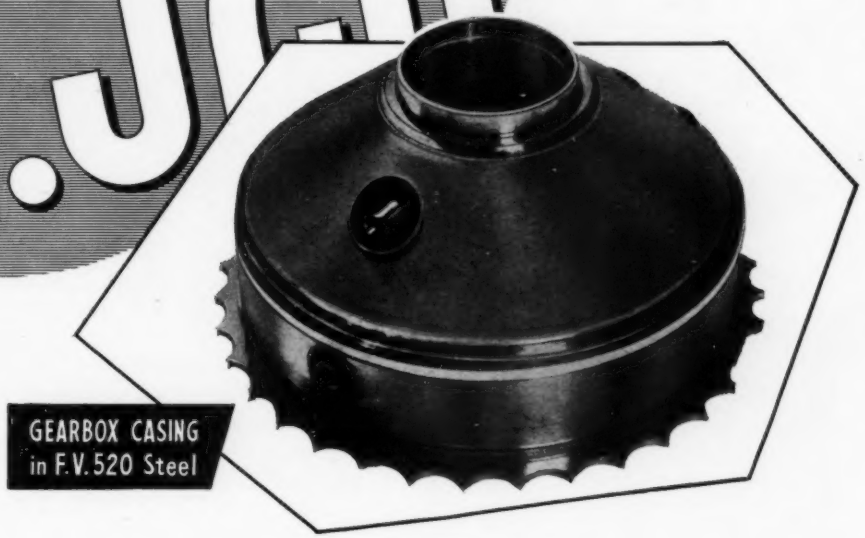

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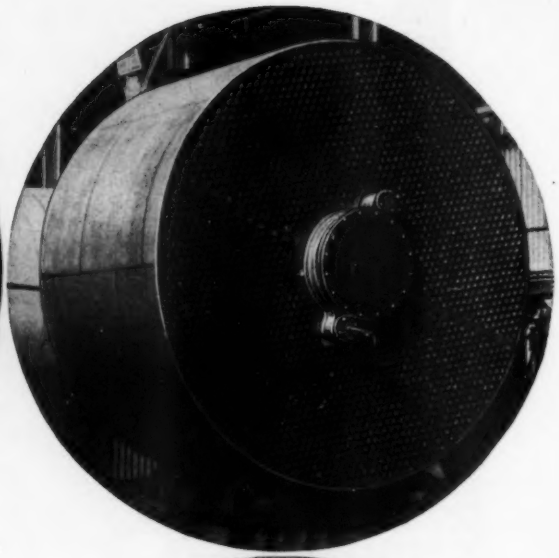

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BK 34A	2400	355	Integral
BK 34B	2400	355	Clamp on
BK 42	600	56	—
BK 42A	600	56	Integral
BK 42B	600	56	Clamp on
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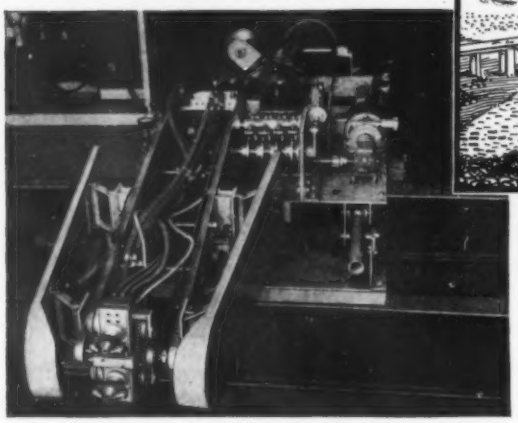

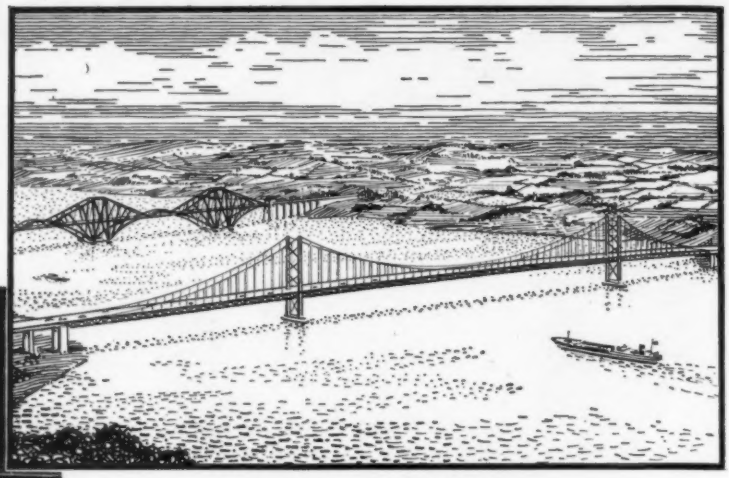

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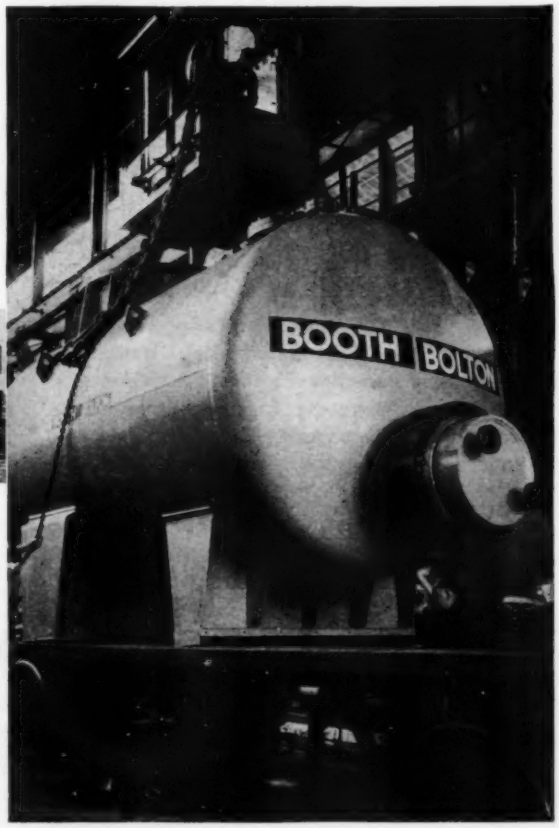

Right: Mild Steel Pressure Vessel for I.C.I.
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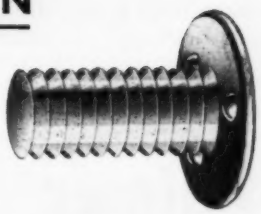

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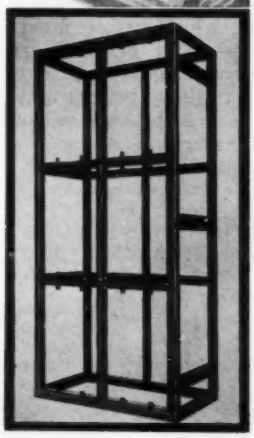

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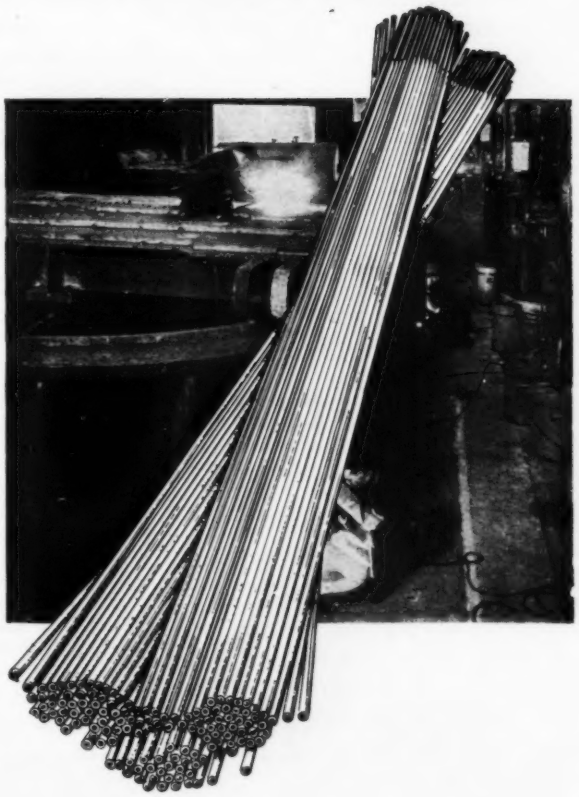

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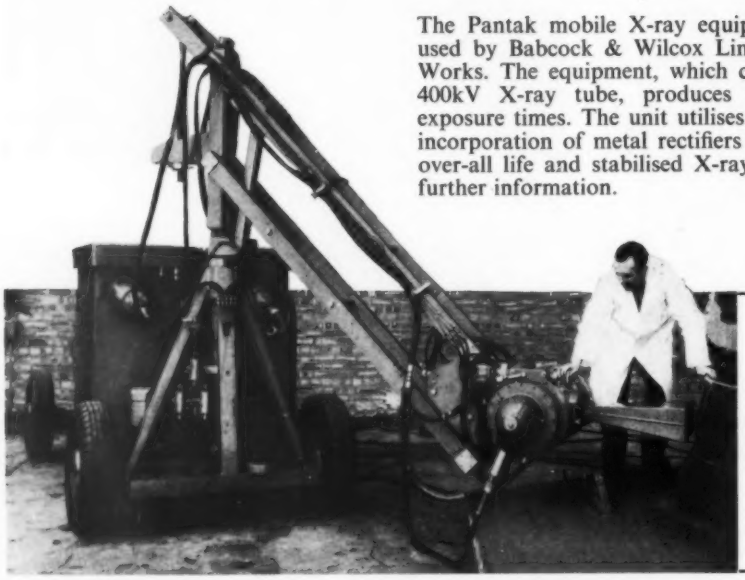

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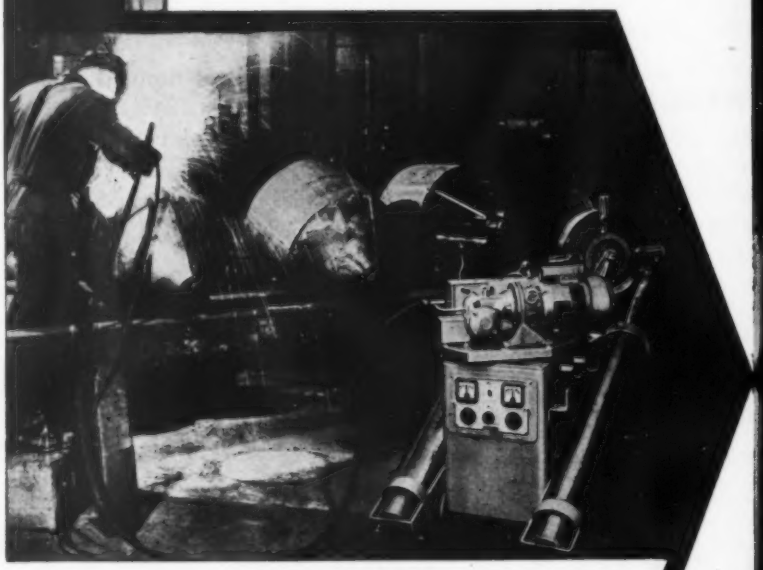

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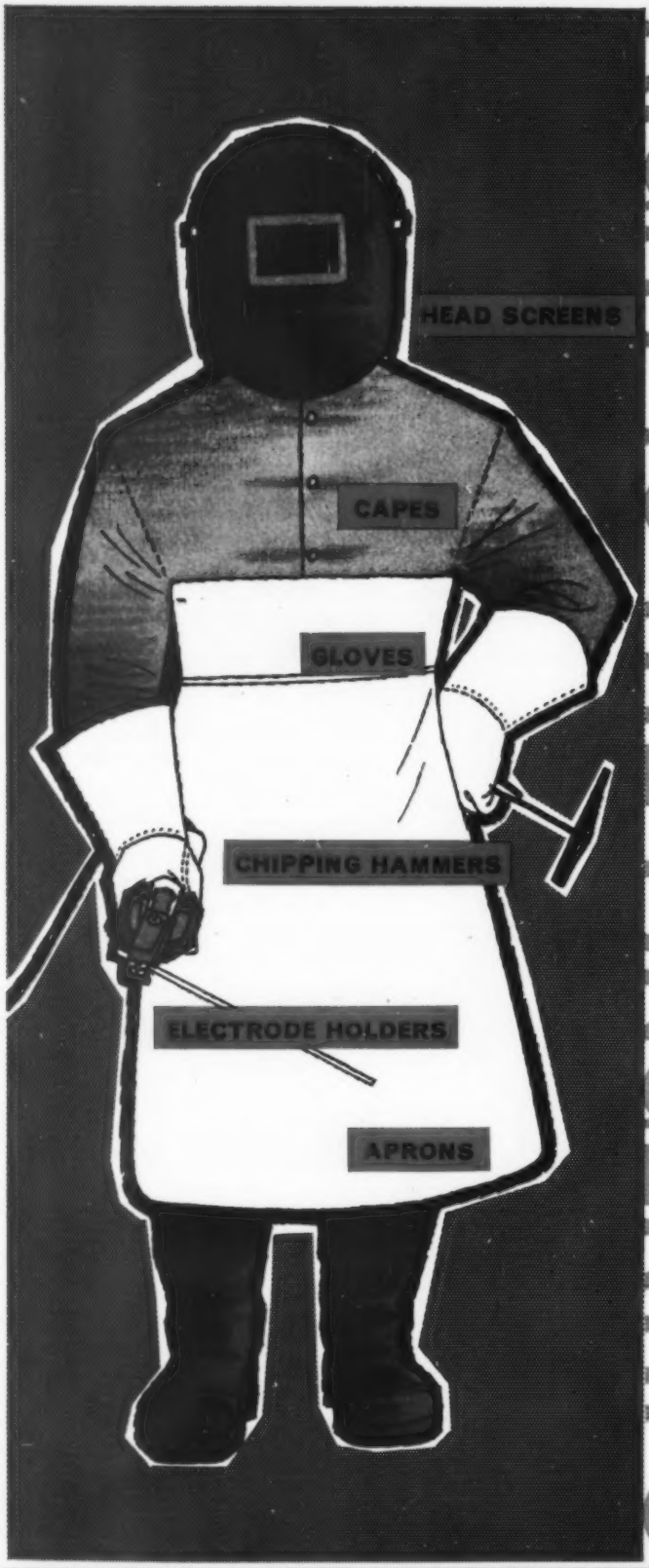

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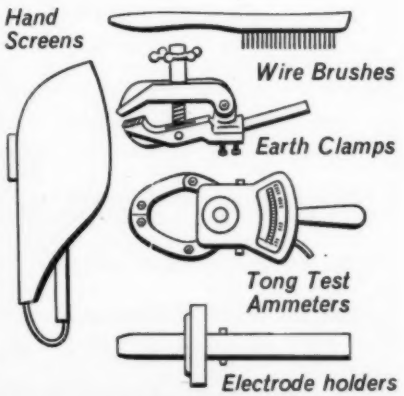

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Welding TECHNOLOGY

UTRECHT MEETING, 1961

Some Design Considerations for Welded Aluminium

By S. R. Banks, M.ENG., *and R. E. Smith*, M.A.

The paper outlines factors relevant to the design of welded aluminium structures.

The characteristics of various aluminium alloys are described, and comparisons are made with structural steel. Typical applications are given.

Static and fatigue strength of welded aluminium joints, and some preferred details of construction, are discussed.

THE AUTHORS do not profess to cover the entire field of welded aluminium design in this paper. They undertake, however, to comment on the characteristics of the wrought materials available, and to deal with a number of matters of design from both the theoretical and the practical aspects. A list of useful references is also included. Welding processes do not fall within the scope of the paper, and it is assumed throughout that the designer is properly advised on appropriate techniques and fillers and that he is able to rely on inert-gas welding (Mig or Tig) of good quality.

The history of welded construction in aluminium is short. In fact it is only within the last fifteen years, and indeed since the inert-gas techniques have been perfected, that engineers have been able to feel confident about the welding of aluminium.

Welding is used in aluminium structures for the same reasons that it is in steel ones, and has the same advantages in terms of economy of material and improved appearance and function. Welding uses less metal than riveting, there is an agreeable absence of overlaps and other clumsy expedients, and fluid-tightness can be readily achieved.

The immense body of experience that has grown up during the welding of millions of tons of structural steelwork during the last half-century is invaluable to the designer in aluminium. No apology is needed, therefore, for the frequent mention of structural steel as a background against which to discuss the problems and prospects of its light-weight competitor.

Materials

Aluminium alloys for welding fall into several well-defined categories. They are listed in the following sections to show the variety of materials that can be welded and also to give a background for discussion of possible lines of development. The materials are dealt with from the United Kingdom viewpoint and are defined in accordance with current British Standards.[1]

Non-heat-treatable materials

These materials derive improved strength by cold deformation only; the deformation may be deliberate (*e.g.* by rolling sheet to a definite hardness), it may be incidental to manufacture (*e.g.* by extrusion), or it may be caused by subsequent forming or other working. The effect of heat, as in welding, is to reduce strength approximately to that of the annealed or fully soft temper; the strength so lost can then be replaced only by further cold deformation.

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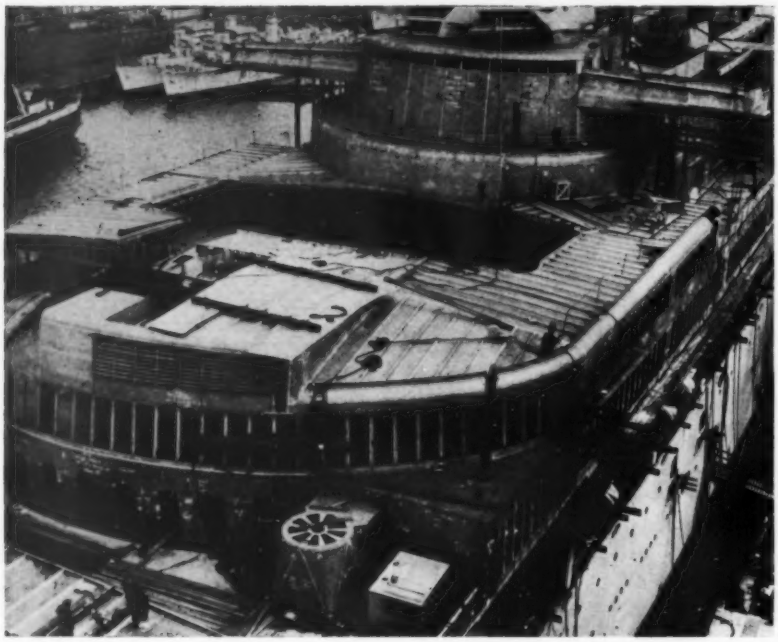


1—*Superstructure of SS* Oriana (*NP5/6*)

Pure aluminium

One non-heat-treatable material is plain unalloyed aluminium, which includes the British Standard materials 1 (99·99% purity), 1A (99·8%), 1B (99·5%), and 1C (99%). These are all highly corrosion resistant, non-contaminating, and readily weldable, and have for many years found wide application in vessels for foods and chemicals. Their scope, however, is strictly limited by strength, which for unwelded material is no more than about 10 tons/sq.in. (15·7 kg/sq.mm) and which, after welding, can be as low as 4 tons/sq.in. (6·3 kg/sq.mm).

Usually considered together with the pure metal is the slightly stronger and almost equally corrosion-resistant alloy N3 (1¼% Mn). This is produced mainly as corrugated sheet for building, in which form it serves a very large market. As a welded material its scope is also limited by its strength.

These purer materials are unlikely to penetrate into many new fields, although mention must be made of their transparency to neutron bombardment which, coupled with the 2 min half life of the radio-isotope Al^{28}, renders them suitable for certain nuclear-energy applications. In one U.K. plant, 1900 tons of welded 1-in. thick plate have been installed.

Al–Mg alloys

The much stronger Al–Mg materials, in contrast, are by far the most important of all materials in welded aluminium construction. They have proved their worth in ship superstructures (Fig. 1), in highway dump-trucks (Fig. 2), in large liquid-gas containers (Fig. 3), and in many other applications ranging from pipelines to highway bridges.

The chief of these materials, listed as N5 (3% Mg) and N6 (5% Mg) and with a long history in

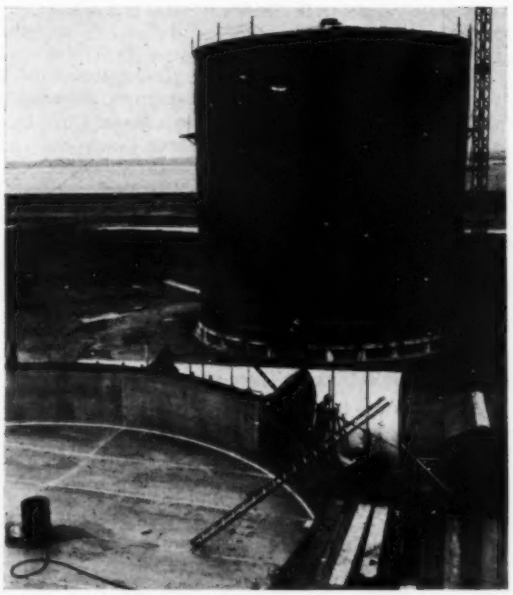
2—*20-ton rock dump-truck* (*AA5456*)

boat-building, first came into general engineering use in about 1950, under the impetus of modern welding methods to which they are ideally suited. In addition to the obvious advantages of lightness and strength, these alloys possess remarkably high corrosion resistance particularly in marine environments. When manufactured in virtually the annealed condition, as they usually are, they suffer very little loss in strength on welding. In fact, this loss is often small enough to be negligible; and it is certainly much less than that occurring with the most efficient riveted joint.

For shipbuilding applications, the plate material NP5/6 (4¼% Mg) was developed in the U.K. a few years ago especially to meet the strength requirements of Lloyd's Register of Shipping[2] with maximum economy. The alloy N6 was retained for sections because its slightly higher Mg content was necessary to obtain the required properties by extrusion.

The almost unlimited scope of the Al–Mg alloys in the range 3%–5% Mg encourages constant search for even marginal improvement in properties, and there is keen competition in the development of new compositions. This is particularly so in the U.S.A., where at present there are six or eight varieties in production, differing from the U.K. materials chiefly in their Mn, Cr and Zn contents.[3] One of these alloys (AA5083; 4½% Mg) is currently being adopted in the U.K. to fill the long-felt need for a single shipbuilding material suitable for both plate and sections. There seems no reason why further developments should not take place.

Finally, a parenthetical reference must be made to two other Al–Mg alloys. One of these is N4 (2% Mg), which has an established use as sheet and panelling; it is stronger than N3, has a similar corrosion resistance, and is equally weldable. The other is N7 (7% Mg) which combines high strength with good weldability and formability, but is of limited use owing to the poor resistance to corrosion, especially under stress, that is associated with its higher Mg content.



3—*Liquid-methane storage tank (NP5/6)*

Heat-treatable materials

These materials derive their maximum strength usually from two successive heat-treatments: a short high-temperature solution treatment with a subsequent rapid quench in water, followed by a more prolonged ageing treatment at a lower temperature with final slow cooling. For materials which age-harden naturally at room temperature, the first heat-treatment (with quench) suffices.

Most heat-treatable materials are weldable (some preferably by resistance welding), but they suffer the disadvantage of significant loss of strength when heated to welding temperatures.

Al–Mg–Si alloys

Until the acceptance of welding as a proved tool for aluminium construction, the Al–Mg–Si alloys H19, H20 and H30 were considered to be the best general-purpose materials for engineering in aluminium. They have a slightly higher ultimate strength (about 10% more) and a considerably higher proof strength (about twice) than N5 and N6; and these properties, in conjunction with a price commonly 10% less, make the Al–Mg–Si alloys economically attractive when strength is the primary consideration. Their relative disadvantages are a somewhat lower resistance to corrosion and a greater loss of strength on welding. This loss, resulting in a localised strength approximating to that of the solution-treated and freshly quenched condition, cannot be replaced except by re-heat-treatment, which is seldom practicable.

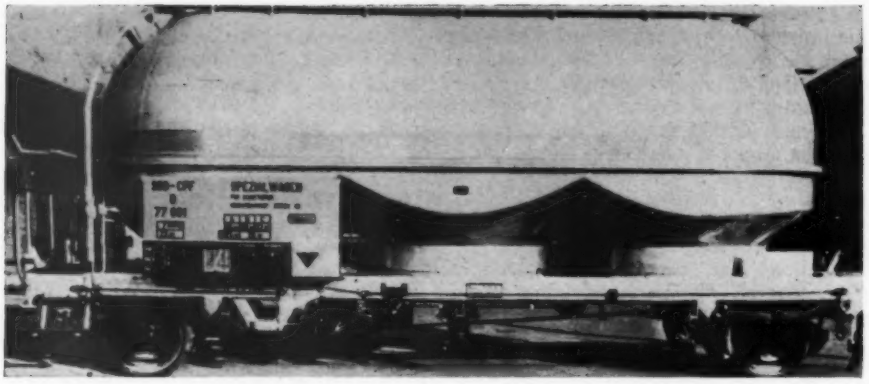
In the same group, though with lower strength, is H9. Because it has a superior natural finish and is readily anodised, H9 has a wide field of use in architecture, where the reduction in strength on welding is often unimportant.

Al–Cu–Mn–Mg(–Si) alloys

Second among the heat-treatable materials are the high-strength copper-bearing alloys H14 and H15 (about 4% Cu, and the latter also containing 1% Si). Their application, with the notable exception of a wide use in aircraft, has been severely restricted by their comparatively high cost and by their comparatively low corrosion resistance when unprotected. Welding of these materials was considered impracticable until recent research by the British Welding Research Association[4] showed that successful metal-arc welds can be made using a 7% Cu–3% Si electrode. It is early yet to assess the effects of this development, beyond noting that possibilities of using copper-bearing alloys may arise in high-strength light-weight structures.

Al–Zn–Mg alloys

Among the most promising of the heat-treatable materials are the comparatively new naturally-ageing alloys of the Al–Zn–Mg type; these are not covered by a British Standard. Together with strength equal or superior to that of the well-known Al–Mg–Si alloys, they possess reasonable corrosion resistance and have the great advantage of regaining strength naturally in the course of a few weeks after welding.



4—*Bulk-transport hopper-car* (*Unidal*) (Courtesy C.I.D.A.)

They were developed in France as "Superalumag T35" (about 3½% Zn and 1½% Mg) and in Germany and Switzerland as "Unidal" (about 5% Zn and 1% Mg) about fifteen years ago; and more recently they have found a variety of uses in several countries. An indication of their possibilities is the Swiss welded hopper-car (Fig. 4) that formed part of an exhibition of aluminium rolling-stock held in Frankfurt in 1960.

Experiment with these materials is on an increasing scale and it is likely that they will assume importance in welded aluminium structures.

General considerations

It is useful, before dealing more closely with design for welding, to draw attention to some of the properties of aluminium that merit special consideration because they are different from those of structural steel. They are mentioned briefly in the following paragraphs; fuller discussion may be found in the literature of the aluminium industry.[5,6]

Cost

Aluminium is more expensive than mild steel; and in spite of its lower specific gravity, an aluminium structure will still weigh about 40% of a steel one and cost several times as much.

Two inferences emerge. The first is that aluminium is an economical choice for structures only when full use can be made of its properties; for example, when its light weight minimises running costs of vehicles, or when its corrosion resistance reduces maintenance. The second inference is that it is desirable to design to greater precision in aluminium because the value of marginal savings is greater than in steel. However, a too-precise design may defeat its purpose by increasing the cost of fabrication, and it is thus necessary to balance these two factors carefully to determine whether or not any particular refinement of weight saving is justified. The saving of a few pounds weight may be economical in an aircraft, for example, but not in a roof truss.

Resistance to corrosion

Aluminium behaves much better than steel in most environments whether rural, urban, industrial, or marine. In fact, in the establishment of an economic case for using aluminium its durability is second only to its high strength-to-weight ratio.

Aluminium structures, particularly in the Al–Mg and Al–Mg–Si alloys, can often be left unpainted. Noteworthy examples are the seven-year-old superstructure of the 13,000-ton cargo ship *Sunrip*, and the ninety London Underground railway coaches that have been in use since 1951; better-known applications are window frames, and corrugated roofing and siding. Painting is usually necessary for Al–Mg–Si materials in severe environments, and is essential for copper-bearing materials in all but unpolluted atmospheres.

The corrosion resistance of welded joints in aluminium is, with ordinary fillers, not significantly different from that of the parent metal, and it is usually unnecessary to give welded joints special protective treatment.

Reference to corrosion is incomplete without noting that aluminium is subject to electrochemical attack if in contact with steel or copper. With steel, painting of the bimetallic joint before riveting or bolting is both necessary and sufficient. With copper (or brass), ordinary painting is insufficient and the two materials must be completely insulated from one another.

Deflection

The modulus of elasticity of aluminium is about one-third that of steel. An aluminium member or framework will consequently deflect about three times as much as a steel one of the same dimensions and under the same loading. This additional deflection is not necessarily a drawback, and discretion must be exercised in any job to make sure whether it is important or not. In a railway coach, for instance, it is; and, generally speaking, the allowable deflection resulting from years of experience in steel must be adhered to, otherwise trouble may be caused by jamming of the doors or by excessive vibration. In a pressure vessel, on the other hand, a temporary increase in diameter may not matter if there is freedom of movement.

Buckling

A further effect of the comparatively low modulus of aluminium is that buckling demands greater attention from the designer than it does in steelwork. An extreme example is a very long strut which, irrespective of alloy, will carry only about a third of the collapse load of a similar steel strut. Aluminium members must therefore be designed with specific regard to the possibility of failure through instability

in compression. Advantage can often be taken of the extrusion process by using special sections with improved efficiency against buckling.[7]

Permissible stresses

Permissible stresses and factors of safety are not so well established for aluminium as for steel, and although a few specifications are available[8,9] the designer may sometimes have to make his own assessment. In doing so, he should take account of both the requirements of the structure and the properties of the material. For static loading, permissible stresses will usually be related to the guaranteed proof stress by a safety factor that can vary from as little as 1·6 for a non-heat-treatable material, where the spread between proof stress and ultimate stress is large (as it is with mild steel), to 2·3 or more for heat-treatable materials with a high proof-to-ultimate ratio. For fluctuating loads, it is not possible to quote permissible stresses; each design must be considered on its merits.

The value of experience and actual testing cannot be over-emphasised, because it will often be found that permissible stresses are of only academic importance. For example, the thickness of the panelling in a bus-body or of the plating in a ship is decided—whether it be by the draughtsman or by some ruling authority—from experience rather than from calculation. In some structures, such as heavy earth-moving vehicles, design is still a matter of trial and error. And in others, the design criterion may well be deflection rather than stress. Even design specifications and codes of practice are in fact compilations of engineering experience, based on performance rather than on strict theoretical reasoning; the use of permissible stresses in struts, for instance, is no more than a convenient way of expressing a long history of testing.

High and low temperatures

It has been noted that the effect of high temperatures is to reduce the strength of aluminium. Therefore any structure likely to be exposed consistently to temperatures of 100°C. or more must be designed at stresses which take into account any consequent weakening of the material. Another high temperature effect is creep; this is significant in the design of pressure vessels.[10]

Sub-zero temperatures on the other hand have no deleterious effects, and in general the properties are improved. It is known[11] that Al–Mg alloys do not suffer from brittle fracture (with rapid crack-propagation) even at −200°C, and experiments by a colleague of the authors indicate that the strength of welded joints, under both static and fatigue loading, increases at low temperatures.[12]

Expansion

The coefficient of thermal expansion of aluminium is roughly twice that of steel. It is therefore essential, in an aluminium structure liable to changes in temperature, that adequate expansion allowance be made, thereby preventing damage either to the structure or to its surroundings. An advantage of the lower modulus is that the actual temperature stresses set up in aluminium are only two-thirds of those in steel.

Appearance

When aluminium is left unpainted it is sometimes necessary to ensure that the appearance of a welded joint is not objectionable. The problem is chiefly met in architectural applications, and a good example is the welded corner of a window frame. Two difficulties can arise. Firstly, the parent material may discolour because of metallurgical changes due to the heat of welding; and, secondly, the appearance of the filler may be in undesirable contrast to that of the parent metal. Both these blemishes are accentuated if the window frame is anodised, and many a fabricator has found to his cost that the welding process and the parent and filler materials must be selected with great care and with expert advice. The best possible appearance with H9 alloy, for example, is obtained by flash-butt welding; but the Tig process also gives good results provided that the material is in the solution-treated condition and is welded with N6 filler.

Resistance to wear

Aluminium is softer than steel and scratches more easily. Nevertheless its resistance to abrasion and shock-damage is frequently better than that of steel. A dump-truck (Fig. 2), for instance, has much longer life when made of aluminium because there are no corrosion products like rust to wear away; and the high resilience associated with the low modulus absorbs a greater proportion of the energy of falling rock, with consequent reduction in damage.

Strength of welded aluminium

Static strength

Typical unwelded and butt-welded tensile strengths of the British alloys are listed in Table I, which shows that the effects of welding are more significant for heat-treatable alloys than for non-heat-treatable ones. For example, the ultimate stress drops from 21 to 12 tons/sq.in. (33·1 to 18·9 kg/sq.mm) for the full strength H30 alloy, but only from 19½ to 17 tons/sq.in. (30·7 to 26·8 kg/sq.mm) for as-manufactured N5/6. Proof stresses are sometimes said to be more affected by welding than ultimate stresses are, but few figures are available for British materials. One difficulty is that the proof stress of a butt-welded joint depends on the gauge length over which it is measured: the longer the gauge length, the higher is the proof stress. Another is the problem of assessing the extent to which a simple tensile test is representative of practical behaviour.

Table I

Typical welded and unwelded strengths

		Ultimate Stress, tons/sq.in. (kg/sq.mm)		
		Tension		
Alloy		*Unwelded*	*Butt-welded*	*Shear on Longitudinal Fillet Weld**
Pure aluminium	S1CH	10 (15·7)	5½ (8·7)	3 (4·7)
Al–Mg	NS3H	13 (20·5)	7 (11·0)	4 (6·3)
	NS4½H	15½ (24·4)	11 (17·3)	6 (9·5)
	NP5/6M	19½ (30·7)	17 (26·8)	9 (14·2)
	NE6M	18½ (29·2)	17 (26·8)	9 (14·2)
Al–Mg–Si	HE19WP, HE30WP	21 (33·1)	12 (18·9)	8 (12·6)
	HE20WP	20 (31·5)	12 (18·9)	8 (12·6)

* Parent metal filler for S1 and NS3; N6 or N21 filler for remainder.

The designer's real need is for knowledge of how an actual structure will behave, and it may often be desirable to test a part of a structure, or perhaps a complete prototype, in order to achieve a fully economic design. The eventual formulation of permissible-stress rules for welded aluminium, therefore, must rely heavily on practical experience. But a rough guide can be obtained by dividing the ultimate weld strengths given in Table I by a factor of about 3.

Typical shear strengths of longitudinal fillet welds are also included in Table I; these depend on the filler rather than on the parent metal.

The local loss in properties of welded aluminium is a considerable drawback but it is not such a disadvantage as it might seem. By careful design it is often possible to locate welds in regions where stresses are low and where the full strength of the material is not required. For example, a beam can be welded along its neutral axis without causing any serious weakness. Similarly, in a built-up girder the web can be spliced near midspan where the shear stress is low, and the flanges at, say, the quarter points where the bending moment is low. And, of course, there is no strength problem in the many applications where welded joints are virtually non-load-bearing and are merely a means of fabrication.

Even when a weld occurs in a highly-stressed region it is still not always necessary to design on the assumption that the whole member is reduced in strength. The actual weakened zone, particularly with automatic Mig welding, is quite narrow and seldom exceeds a few centimetres in width, even with heat-treatable material. In tension members, a longitudinal weld will have very little effect on overall strength; a transverse weld, on the other hand, will inevitably produce a weak cross-section which must be taken into account. For this reason longitudinal welds are preferable to transverse ones when static strength governs the design. A valuable design method,[13] corroborated by tests,[14] has recently been developed in the U.S.A. This method allows for the reduction in strength near welds, but at the same time takes advantage of the inherent strength of the material remote from welds. It is worthy of study by all designers of welded aluminium.

Design is greatly simplified if use can be made of the naturally-ageing alloys, such as H14 and more particularly the newer Al–Zn–Mg series, which regain their strength after welding.

Fatigue strength

Fatigue is a complex phenomenon, and in the present state of knowledge it is possible to make only very limited rulings on permissible stresses for welded joints.[9] Nevertheless the factors governing the fatigue behaviour of welded aluminium are becoming understood,[15,16] and can be summarised as follows.

The maximum load used for static design rarely occurs in the life of a structure and is of little interest when fatigue performance is being assessed. It is the many-times-repeated live load, perhaps superimposed on a steady dead load, that is important. For example, an N5/6 butt-welded joint will fail under a static tensile stress of 17 tons/sq.in. (26·8 kg/sq.mm); but the same joint carrying a constant stress of 3 tons/sq.in. (4·7 kg/sq.mm) will fail after about one million applications of a further stress of ±3 tons/sq.in. (±4·7 kg/sq.mm). Great care must be taken in estimating both the magnitude and the frequency of loading. On the one hand underestimation may lead to premature failure, while on the other hand exaggeration can easily result in rejection of a design on economic grounds.

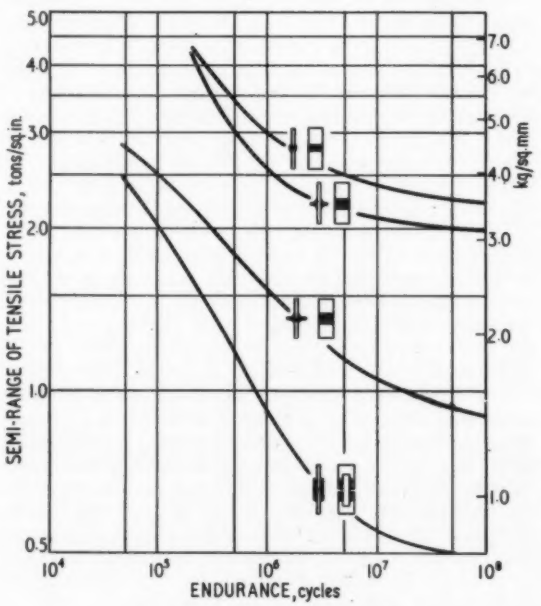
One of the most important factors in designing against fatigue is the actual geometry of the welded joints. Careful detailing is essential to avoid the stress concentrations which are the prime cause of fatigue failure. Unsymmetrical or eccentrically loaded joints and sudden changes of cross-section are bad in fatigue; and so are stress raisers such as weld craters or intermittent welds. The importance of joint design is illustrated by some test results (Fig. 5) obtained by another of the authors' colleagues.[17] Butt-welded joints, provided they are of smooth profile and free from undercutting, give the highest fatigue endurances.

The requirements of design against fatigue are often in conflict with those for static design. Thus transverse fillet welds, with their more uniform stress distribution, are superior to longitudinal ones in spite of the adverse effect on the static strength of the members being joined. Again, cover straps or excessive weld deposits that are useful for improving the static strength of a joint will actually reduce its fatigue properties.

Much guidance on design against fatigue is available from the aluminium industry, but often the only sure way of solving a particular problem is by fatigue testing joints, or even complete structures, made as nearly as possible identical to those actually proposed, and loaded under the expected working conditions.

Details of design

Apart from the initial problems of choosing the appropriate alloy and welding process for any



5—Fatigue strength of NP5/6 joints

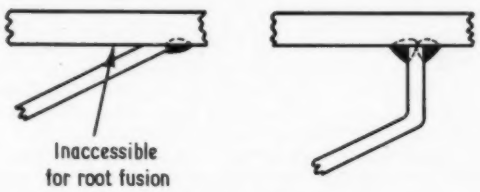
particular application, there are several considerations which the designer should bear in mind.

Firstly, close liaison with the welding shop is essential; otherwise the welder may not understand exactly what the designer wants, and the designer may not be able to take full advantage of the welder's practical experience. It is not enough for the draughtsman to depict two pieces of metal on a drawing and accompany them merely with the word "WELD". Details of joints should always be given in full, preferably by means of standard symbols[18] which should be known by both parties. A good design in welded aluminium demands a clear understanding of methods of construction, and the welder himself will often be able to suggest expedients that will minimise fabrication difficulties. Furthermore, the welder's views on accessibility to the torch, on elimination of unnecessary jigging and handling, and on welding sequence to control distortion should also be obtained and incorporated in the design from the outset.

Such matters as the avoidance of misalignment or even of undercutting at welded joints, and the provision of run-off tabs to eliminate weld craters (in addition to drawing-board matters like the avoidance of abrupt changes in cross-section and of crevices which may encourage corrosion) are the responsibility of the designer, who must also ensure by precise specification that his requirements of weld testing and inspection[19] are fully stated and will be properly met.

Obviously, the number of welded joints should be kept as small as possible, so as to improve the appearance of the finished job. Fabrication will also be much cheaper.

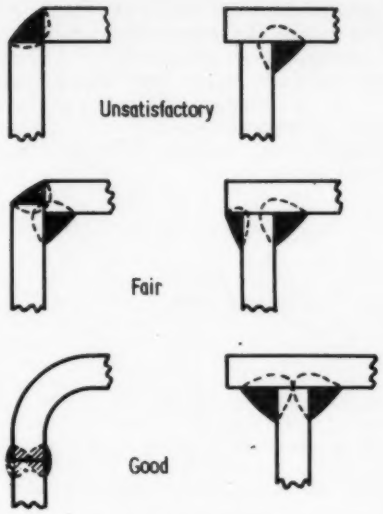
All joints should be kept simple and, as far as possible, arranged either for mechanised welding or for manual welding in the downhand position. Awkward joints can often be avoided by the use of special extrusions, forgings or castings, or simply by bending the various components. Thus, when two plates forming a T-junction meet at a very acute angle (Fig. 6), it may be preferable to bend one of them so that the joint is fully accessible to the welding torch. Ideally,



6—*Acute-angled T-junction*

joints should be self-jigging and arranged so that the neighbouring metal provides adequate support for the molten weld pool. For example, in plate-to-stiffener assemblies it is convenient, when butt welding the plate, to use the stiffeners themselves as backing bars.

Some simple corner connections are illustrated in Fig. 7. Single fillet welds on one side of a T-joint are weak against tearing from the root and produce undesirable notch effects; welding should be done from both sides. When strength is important, sufficient overlap should be provided (greater than the fillet size)



7—*Simple corner welds*

to prevent burning away of the corner and so avoid an undersize throat of the fillet weld.

With fillet welds, it is worth remembering that strength is proportional to throat size but that cost is proportional to the square of throat size. Therefore, a continuous small fillet will be cheaper than an equivalent large intermittent one, as well as being more satisfactory from the viewpoints of watertightness, of absence of corrosion crevices and stress concentrations, and of suitability for automatic welding.

With butt welds, full consideration should be given to eliminating expensive edge preparation whenever possible. If material can be ordered precisely to size, and even pre-sawn at the correct angle, appreciable savings can be made. Furthermore, edge preparation can sometimes be dispensed with if advantage is taken of the recently developed high-current Mig process for thick plate.

Concluding Remarks

To take a broad view, it can be said that although welding is a proved technique for aluminium structures its application is not yet fully exploited. However, there are indications that welded aluminium will enter more widely into road, rail and sea transport and, with increasing knowledge of the static and fatigue properties of fillet-welded joints, into framed structures.

In materials, the already-successful Al–Mg alloys with Mg-contents between 3% and 5% are likely to be developed and improved; and the newer Al–Zn–Mg alloys, with their ability of recovering strength after welding, are also expected to come into prominent use.

In design, perhaps the most important point is that no welded aluminium project should go forward without prior and continuous liaison between drawing office and welding shop.

To encourage new developments it is incumbent on the aluminium industry, with the help of the welding

institutions, to place up-to-date knowledge of welded aluminium before the engineering profession in the form of clear and easily usable design information and to do this as quickly and as continuously as possible. Much of this information is already available from aluminium manufacturers, and the designer can obtain considerable assistance from their experience and research work.

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BOOK REVIEW

A. MATTING (*ed.*): "*Das Schweiszen der Leichtmetalle und seine Randgebiete*", 1959, Düsseldorf, Deutscher Verlag für Schweisstechnik, 200 pp. (19.50 DM.)

This Handbook is the second edition of the well-known work which was first published immediately before the outbreak of war in 1939. Both editions have been edited by Professor A. Matting of the Technical High School, Hanover, and the work is, as may be expected, extremely thorough. This edition contains contributions from many of the light metal welding experts in Germany and can be recommended as a useful summary of the state of the science in that country. The seventeen chapters cover not only the welding processes for aluminium and magnesium but also the allied topics of joining by plastics adhesives, metal spraying and cutting processes, testing and design recommendations. Only one chapter is devoted specifically to the welding of magnesium alloys and this might well have been expanded, especially in view of the early and continuing interest of German industry in magnesium.

The first chapter provides a brief but valuable summary of the applications of the various joining processes to aluminium and its alloys which are set out according to the German (DIN) specifications, and these recommendations follow largely the same lines as those current in Britain. There is a brief explanation of the basic metallurgical factors which influence the tendency to weld cracking, and tribute is paid to the considerable amount of British work in this field. The effects of temperature on the properties of the parent metal are well illustrated, and there is a useful note on the indentification of the light alloys—a contribution which might well appear in other books on this subject. Gas welding and metal arc welding are still prominently featured, but the chapter on inert-gas welding is perhaps a little thin when account is taken of the very large amount of information published in the English-speaking countries. The author's treatment of electric resistance welding is excellent, as also is the chapter on jointing of cables; this last, incidentally, being the only chapter which bears no author's name. Soldering is given a chapter to itself, and does not list the usual large selection of solder compositions or of flux mixtures.

Perhaps the most interesting contribution is by Matting himself on 'special' welding processes which range from hammer welding to pressure welding, including a reference to the fundamental work by Tylecote in Britain. The application of this process to heat exchangers developed for war-time purposes is well illustrated and the chapter includes a brief description of the 'Alfin' process for bonding aluminium to steel and cast iron. There is a separate chapter on cold pressure welding, the applications cited including solid rod conductors. What may be properly described as a powerful chapter is by Brenner and Matting on the way to apply welding, and some quite useful design data are provided. Matting also collaborates with Klein on testing of light metal welds, providing a useful summary of practice.

Although some of the illustrations might have been larger, with advantage the book is well produced and forms a useful guide to practice in Germany.

E. G. WEST

UTRECHT MEETING, 1961

A Recent Specification for Fusion Welded Aluminium and Aluminium Alloy Pressure Vessels for Class I Duties

By F. Smith

The paper discusses the major technical points involved in the drafting of a specification for Class I fusion-welded aluminium and aluminium-alloy pressure vessels. The specification has been prepared by Imperial Chemical Industries Ltd. for the purchase of chemical process vessels in these materials.

Introduction

It is standard practice in Imperial Chemical Industries Ltd. to purchase pressure vessels to internal company specifications which cover their manufacture, inspection, and testing; inspection is carried out by the company Inspectorate at certain defined stages during fabrication. Methods of design and of fabrication for mild steel and Cr–Ni steels are well established, and specifications to cover the purchase of vessels in these materials have been available for a number of years. However, the purchase of a pressure vessel in aluminium or its alloys has been conducted on an individual basis for each vessel. The specification to be discussed has been prepared so as to minimise work in the design and ordering stage and to standardise the basic requirements for pressure vessels in these materials.

It is emphasised that the document referred to is a Company specification and is not a British Standard Specification.* As such, it is concerned solely with the Company's requirements for pressure vessels in aluminium and its alloys. The document has been prepared by a small panel, composed of Company staff, and the author is one of the members of this panel. Acknowledgement of helpful advice is made to Messrs. A.P.V. Ltd. with whom the draft was discussed.

Since a specification is a contract document, whose requirements are legally binding on both purchaser and contractor, a number of points of detail must be covered. These will of course include matters common to pressure vessels in other materials. In this paper only the major points, specific to the design, fabrication, and/or testing of vessels in aluminium or its alloys will be discussed.

Relevant sections of the specification are given in the Appendix together with a number of typical weld details.

*A British Standard Specification for Aluminium and Aluminium Alloy Pressure vessels is in the course of preparation.

Manuscript received 6th March, 1961.

The author is in the Research Dept., General Chemicals Division of Imperial Chemical Industries Ltd., Widnes.

Discussion

Design

Whilst BS.1500:1958, Part I "*Fusion Welded Pressure Vessels for use in the Chemical, Petroleum and Allied Industries*" deals only with the design, construction, and inspection of pressure vessels in carbon and low-alloy steels, the design methods in this document are suitable for use in the design of aluminium and aluminium-alloy pressure vessels with some slight exceptions and qualifications. The additional requirements are:

(*a*) *Allowable Design Stresses*

Allowable design stresses for substitution in the relevant formulae in BS.1500 are given in the specification.

The stresses for plate and other wrought material were obtained partly from the ASME Code for unfired pressure vessels (Section VIII 1956). The remainder were derived from test data available in the United Kingdom, the criteria used in deriving the allowable stresses being those given for non-ferrous metals in the ASME Code.

Some of the materials allowed by the Company Specification do not give joints whose strength invariably exceeds the minimum annealed strength of the parent plate, and to take this into account the design stresses for butt welds in tension are reduced to 95% of those permitted for the material in the annealed condition.

(*b*) *Vessels Subject to External Pressure*

The design formulae and methods given in BS.1500:1958, Part 1 are not applicable to the design of aluminium or

aluminium-alloy vessels which are subject to external pressure, since the values of Young's Modulus and of the yield stress for the various steels are written into the design methods. The requirements of the ASME Code 1959 have therefore been specified.

(*c*) *Weld Details*

A number of weld details for aluminium and its alloys have been prepared which are suitable for Tig and Mig processes.* Typical details, which include types suitable for both pressure vessels and light duty fabricated items, are given in the Appendix. Where vessels are designed by a contractor copies of standard sheets giving these weld details will be supplied with the order. This is normal Company practice.

The design of butt weld details in these light metals follows standard practice, the difference between them and those for mild steel being due to the need to provide access for the welding torch nozzle, particularly with the Tig process. Suitable access is provided by increasing the included angle of the weld detail and the root radii in the case of thick sections.

Groove welds in flanges and other attachments are similarly increased in width to allow access.

As in the case of steel, welds in fillet-welded attachments are sized so that the effective throat thickness is equal to the thinner member of the sections being welded.

(*d*) *Stress Relief*

It is not considered necessary to heat-treat fusion-welded aluminium vessels for stress relief.

Materials

The materials included in the specification are those considered to be suitable for the manufacture of fusion-welded Class I pressure vessels. The Al–Mg–Si alloys are omitted, partly for reasons of poor weldability but also for design limitations, since the annealed strength of these materials, which is approached in the heat-affected zone in welds, is significantly lower than the annealed strength of the high-magnesium non-heat-treatable alloys such as N4, N5 and N5/6. Since it is not normally practicable to heat-treat fusion-welded pressure vessels of Al–Mg–Si alloys to develop their optimum strength, there is no advantage to be gained in their use.

The materials allowed are therefore as follows:

99·99%	aluminium to BS.1470 and 1477	Alloy 1
99·8%	" " " " "	Alloy 1A
99·5%	" " " " "	Alloy 1B
99·0%	" " " " "	Alloy 1C
1·25%	manganese alloy to " " "	Alloy N3
2·5%	magnesium " " " " "	Alloy N4
3·5%	" " " " " "	Alloy N5
4	" " " " " "	Alloy N5/6

Alloys N5 and N5/6 are, however, limited in their application, since it has been shown[1] that alloys containing more than about 3% Mg are liable to form a grain-boundary precipitate when heated at even moderately elevated temperatures. Precipitation increases with increase in magnesium content and is more rapid in the cold-worked condition than in the annealed condition. The precipitated phase (Al–Mg) is strongly anodic to the grains and can corrode selectively at high rates in the presence of an electrolyte, particularly under the influence of stress. Both wrought and cast magnesium alloys, including weld deposits, are susceptible to precipitation during heating and to intergranular attack. The use of the high-magnesium alloys N5 and N5/6 has therefore been restricted to those vessels whose subsequent service temperature will not exceed 40°C. Preheating of these alloys during fabrication is not permitted for the same reason.

The alloy N4 is not susceptible to grain-boundary precipitation and subsequent intergranular corrosion owing to its low magnesium content (1·8–2·7%). However, this material is normally welded with N6* filler rod which contains 4·5–5·5% Mg. For vessels in N4 which are intended for service at temperatures above 40°C., N4 filler rod must be used. Guidance to this effect is given in the Foreword to the Specification. The reduction in magnesium content of the filler rod results in the weld deposit being crack sensitive under conditions of restraint, *e.g.*, as in the case of branch attachment welds and patch welds. It is, however, possible to make crack-free butt welds, and for this particular case it is recommended that fillet-welded attachments be avoided in design, *e.g.*, by swaging out branch connections to allow butt welding of welding-neck flanges.

Fabrication

Only the Tig and Mig welding processes may be used for the fabrication of vessels to this Specification, the metal-arc process using covered electrodes and the oxy-acetylene process being considered unsatisfactory.

It may be noted that aluminium of 99·5% purity (Alloy 1C) is specified for vessels for some nitric acid duties and that hot-hammering of welds is necessary to disperse grain-boundary Fe–Si precipitates when the oxy-acetylene and/or metal-arc process with covered electrodes are used in the fabrication of the vessels. It has been shown within the Company that hot-hammering of welds is not required if the Tig or Mig processes are used with 99·8% purity filler rod or wire.

Inspection and Tests

Mechanical Tests

Test plates attached to the vessel and welded by the same process and at the same time as the vessel seams are specified as in standard practice. The all-weld-metal tensile and the impact test normally demanded on mild steel vessel test plates are not considered to be necessary in the case of aluminium, since weld deposits are not subject to fissuring, a factor which can seriously affect reduction in area values, or to embrittlement. A side-bend test was, however, specified in place of the more usual direct and reverse bends, since it was considered more likely to reveal centre-line faults. Aluminium and Al-Mn welded joints are sufficiently ductile to permit bending around a former of 3*T*, where *T* is the width of the side bend test specimen. However, the ductility of weld deposits in N4, N5 and N5/6 is much lower, and for these materials a former of 6*T* is specified.

Radiography

Although radiographically sound welds can be obtained in aluminium or the Al–Mg alloys, they cannot be consistently achieved as in mild steel vessels fabricated to Class I standards. Furthermore, repair welding of defective mild steel welds can be carried out with comparative certainty whereas attempts to

*Tig = inert-gas tungsten-arc process.
Mig = inert-gas metal-arc process.

*BS.2901 Alloy NG6.

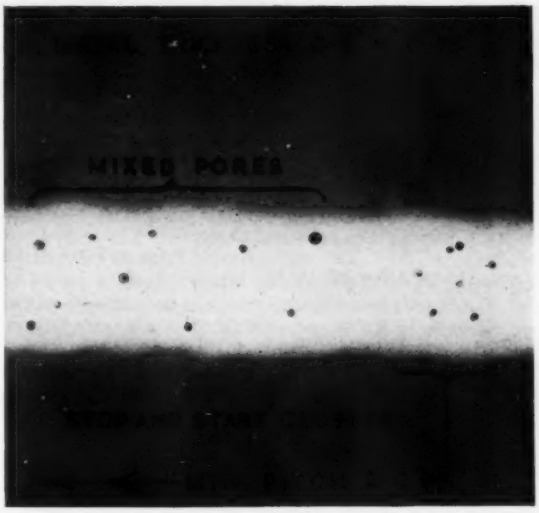
repair minor gas porosity in aluminium or aluminium-alloy welds may result in the incorporation of more serious defects in the seam. With aluminium or aluminium-alloy butt welds, it is therefore undesirable and often impracticable to insist on complete freedom from minor porosity, and the radiographic standard of such welds must differ from that customary in Class I mild steel vessels, *i.e.*, virtually clear radiographs.

Radiographically sound welds in mild steel can be achieved consistently only by the use of a suitable welding procedure, attention to detail, and good technical control. A radiographic standard of acceptance for aluminium butt welds in vessels for Class I duties must represent a standard that can be achieved by similar good practice. A standard that is set too low is undesirable however, for it provides no incentive to further process improvement and is otherwise unsatisfactory for competent contractors. It should also be noted that welds can contain defects which are difficult to detect even by good radiographic techniques. An excessively high standard of acceptance is equally undesirable. When drafting the radiographic acceptance clause careful consideration was given to both the above aspects.

A number of faults which are considered to be unacceptable are listed in the relevant clause in the Specification. These faults include cracks, lack of fusion, lack of penetration, and aligned porosity, the latter being indicative of undetected lack of penetration. All these faults would have a serious effect on the strength of a welded seam. The remaining faults in this class, *viz*, tungsten inclusions (Tig only), oxide inclusions, and porosity in the size range noted are considered to be avoidable by the use of suitable welding procedures. But these defects are almost inevitably present to some extent in all welds and the radiographic acceptance standard is primarily concerned with these.

Tungsten inclusions can occur as isolated spots or as colonies. They are not completely avoidable but it is considered that the limits proposed in the acceptance standard represent the maximum inclusion count which would occur with the use of a correct welding procedure. Oxide film limits were arrived at on a similar basis.

The selection of a radiographic standard of acceptance for porosity is complicated by the fact that the various grades of aluminium (including the Al–Mn alloy) have a narrow freezing range and are inherently more prone to gas porosity in welding than are the Al–Mg alloys which have a wide freezing range. Furthermore, the freezing rates of weld deposits are higher with the Mig than with the Tig process; in consequence welds made by the former process tend to be more porous than Tig welds. However, with the Mig process, sound welds can be made in the Al–Mg alloys which show only isolated patches of porosity. After consideration and examination of a number of radiographs of welds it was decided that continuous random porosity can be avoided in these materials



1—*Diagram simulating radiograph with maximum porosity considered acceptable for weld in Class I aluminium pressure vessel*

and that porosity should be limited to 10% of the seam length to represent good welding practice. This allows for any process variations in welding which tend to produce porosity. Increased porosity at stops and starts, including repair welding, is catered for as additional allowable groups of pores. The reduction in volume attributable to the porosity allowed is less than 0·5%, *i.e.*, below that at which a significant reduction occurs in the mechanical properties of the welded seam.[2]

With the various grades of Al and the Al–Mn alloy it is not realistic to demand the foregoing standard except possibly in the case of thin plate welded by the Tig process. Continuous random porosity in the range noted is therefore allowed over the whole of the seam in these materials.

A radiographic acceptance standard of the type given in the Specification is difficult to apply in practice and it has been concluded that the best way of assessing the standard of a given weld would be to provide the inspector with a set of standard radiographs which show the allowable limits of porosity. These radiographs can be used directly for comparison with the radiograph under examination. Such standard radiographs can be produced cheaply and rapidly by painting a clear master radiograph and making a positive from this. A typical reproduction made by this technique is shown in Fig.1. It is intended to produce sets of these radiographs for use by the Company Inspectorate and by the contractor, if so desired.

REFERENCES

1. E. H. Dix, W. A. Anderson, M. Byron Schumaker: *Corrosion*, 1959, vol. 15, pp. 19–26.
2. "Classified Radiographs for Defects in Aluminium Welds". B.W.R.A. Booklet H3, 1958.

(*Appendix follows on p. 210*).

APPENDIX

Relevant Sections of Specification

PART I—DESIGN

1. Design Code

Vessels to this Specification shall be designed in accordance with BS.1500, Pt.1 "Fusion Welded Pressure Vessels for Use in the Chemical, Petroleum and Allied Industries" with the exceptions noted in Clauses 2–9 and as indicated in the Company's enquiry and order.

2. Maximum Allowable Design Stresses

(*a*) *Plates and other Wrought Material (excluding bolts) in Tension*

The design stress for plates or other wrought material (excluding bolts) in tension shall not exceed the values given in Table 1 of this Specification for the material(s) specified on the Company's order for the fabrication of the vessel (See also Part II, Clause I).

The design stresses shall be substituted for $f \times J$ in equations (3) to (6) on page 29 of BS.1500 to determine the value t_v when this value is required for substitution in Equations (24) to (26) on page 57.

(*b*) *Butt Welds in Tension*

The allowable design stress for butt welds in tension shall not exceed the values given in Table 2 of this Specification for the materials to be used in the fabrication of the vessels.

These design stresses shall be substituted for $f \times J$ in the following formulae of BS.1500:

Equations (3) to (6) (page 29), (15) and (16) (page 36) and (18) and (19) (page 42).

(*c*) *Butt Welds in Compression, External Pressure*

The maximum allowable stress in compression in wrought material or butt welds shall not exceed $\frac{3}{4}$ of the values given in Tables 1 and 2 for the particular material to be used.

For vessels subject to external pressure the design requirements should be those given in Section VIII of the "ASME Boiler & Pressure Vessel Code" 1959, Clauses UNF-23, UNF-30, UNF-33, and the charts given in Appendix V of this Code. The out-of-roundness tolerances in Clause UG-80 of this Code shall also apply to such vessels (See Pt.IV, Clause 13).

(*d*) *Bolting Materials*

For internal bolted fittings on vessels intended for duties which do not permit the use of chromium-nickel austenitic bolts, the bolting material shall be N4 or N6 according to the operating temperature of the vessel. The design stresses for these are given in Table 3.

(*e*) *Young's Modulus*

Values of E for aluminium and its alloys over the temperature range 0°C. to 200°C. are given in Table 4.

3. Weld Details

The dimensions of all welding grooves and the finished welds shall conform to D.O. Standard Sheets XXX except where otherwise agreed in writing. All welds shall be separately detailed and fully dimensioned on the approved drawing.

4. Openings, Branches and Compensation (See Section Three J. BS.1500 pages 57–70)

Where branches of the type shown in Fig. 32.0 of BS. 1500 are to be fabricated from a separate plate for subsequent butt welding into the vessel shell, the plate shall be as large as is practical and the butt welds shall be inspected, radiographed and approved. The butt welds between the swaged-out branch and the attached pipe or weld neck flange, should be radiographed whatever the method of producing the branch (See Pt. IV, Clause 5 (b)).

Table 1

Aluminium and Aluminium Alloys

Maximum allowable design stresses in tension (lb/sq.in.) for plates and other wrought material (excluding bolts)

Alloy Designation	*Description of Alloy*	*Temper*	*Design Stresses for Temperatures not Exceeding:* 40°C.	100°C.	150°C.	175°C.	200°C.
1	99·99% aluminium	O	1490	The Division Metallurgical Authority should be consulted for design stresses in this temperature range			
		½H	2800				
		H	3620				
1A	99·8% aluminium	O & M	1730	1500	1200	1000	800
		¼H	3350	2500	2000	1000	800
		H	4470	3500	2000	Not recommended	
1B	99·5% aluminium	O & M	1930	1790	1250	1200	1050
		¼H	3620	2900	2350	2000	1600
		H	4750	4000	3750	Not recommended	
1C	99·0% aluminium	O & M	2660	2300	1850	1600	1300
		¼H	3350	3150	2650	2400	2100
		½H	3900	3650	3000	2700	2200
		¾H	4470	4000	3600	Not recommended	
		H	5000	4500	4250	Not recommended	
N3	1¼% manganese alloy	O	4000	2900	2400	2100	1800
		¼H	4200	3800	3300	3000	2650
		½H	5020	4700	4000	3500	3100
		¾H	5870	5200	4800	4200	3600
		H	6420	5800	5600	5000	4150
N4	2½% magnesium alloy	O & M	6150	6100	5400	4650	3900
		¼H	7270	7200	6400	5600	4800
		½H	8400	8400	6900	6100	5300
N5	3½% magnesium alloy	O & M	7820	These high magnesium alloys are not recommended for use in this temperature range			
		¼H	9500				
N5/6	4% magnesium alloy	O & M	9500				

1000 lb/sq.in. = 70 kg/sq.cm (approx.)

Butt welds between the following parts shall also be radiographed:

Weld neck flange to vessel
Weld neck flange to branch pipe
Weld neck flange to swaged branch
Branch pipe to swaged branch.

5. Bolted Flanged Connections

These shall be designed in accordance with the standards specified in the Company's order and/or drawing.

6. Jacketed Vessels

(*a*) *Jacket Attachment*

The details of jacket attachments shall be agreed with the Ordering Authority.

(*b*) *Sequence of Fabrication*

This shall be determined by consultation between the Ordering Authority and Contractor. The approved drawings shall indicate the order of procedure in every case where it is necessary for the steps in the manufacture to be performed in a certain sequence. This shall include:

(i) The stages at which inspection is required (See Pt. IV, Clause 1)
(ii) The stages at which pressure tests are to be applied
(iii) Any deviations from the requirements of this Specification.

7. Stress Relief

Heat treatment, for stress relief, is not required for vessels fabricated in accordance with the requirements of this Specification.

8. Domed Ends

The shapes and dimensions given in BS.1966, "Domed Ends for Tanks and Pressure Vessels" shall apply.

Table 4

Aluminium and Aluminium Alloys
Moduli of Elasticity
(Modulus of elasticity = $E \times 10^6$ lb/sq.in. (kg/sq.cm))

E *for Temperature not exceeding:*				
40°C.	*100°C.*	*150°C.*	*175°C.*	*200°C.*
10·6 (0·745)	10·4 (0·731)	10·2 (0·717)	10·0 (0·703)	9·7 (0·682)

9. Support During Hydraulic Test

Unless otherwise specified in the Company's order, the vessel shall be designed so as to permit the hydraulic test pressure to be applied with the vessel full of water in the erected position.

PART IV—INSPECTION AND TESTS

1. Inspection

The Company's Inspecting Engineer or other authorised representative shall have free access to the Works of the Contractor and Sub-Contractors at all reasonable times. He shall be at liberty to inspect the manufacture at any stage, and to reject any material that does not conform to the terms of this Specification. Rejected material will not be accepted or paid for by the Company.

The Company reserves the right to make a careful examination by either visual or other means at any suitable stage of the work. Parts showing evidence of bad pick-up, tungsten or copper inclusions, porosity or other detrimental features shall, on the instructions of the Company's Inspecting Engineer, be cut out and re-welded.

In all cases, inspection will be carried out at the following

Table 2

Aluminium and Aluminium Alloys
Maximum allowable design stresses (lb/sq.in.) for butt welds in tension

Alloy Designation	*Description of Alloy*	*Design Stresses for Temperatures not Exceeding:*				
		40°C.	*100°C.*	*150°C.*	*175°C.*	*200°C.*
1	99·99% aluminium	1420	The Division Metallurgical Authority should be consulted for design stresses in this temperature range.			
1A	99·8% aluminium	1640	1420	1140	950	760
1B	99·5% aluminium	1830	1700	1190	1140	1000
1C	99·0% aluminium	2520	2180	1760	1520	1230
N3	1¼% manganese alloy	3800	2760	2280	2000	1710
N4	2½% magnesium alloy	5840	5790	5130	4420	3700
N5	3½% magnesium alloy	7430	These high magnesium alloys are not recommended for use in this temperature range.			
N5/6	4% magnesium alloy	9000				

1000 lb/sq.in. = 70 kg/sq.cm (approx.)

Note: These design stresses for butt welds apply irrespective of temper of parent plate.

Table 3

Aluminium and Aluminium Alloys
Maximum allowable design stresses for bolts for aluminium alloy bolts for internal fittings

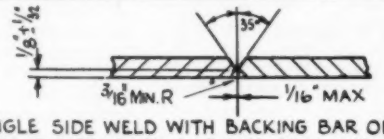
Alloy Designation	*Temper*	*Minimum Ultimate Stress* lb/sq.in. (kg/sq.cm)	*Minimum 0·1% Proof Stress* lb/sq.in. (kg/sq.cm)	*Design Stresses for Temperatures not Exceeding:*				
				40°C.	*100°C.*	*150°C.*	*175°C.*	*200°C.*
N4	½H	33600 (2370)	26800 (1885)	6700 (470)	6700 (470)	6700 (470)	6100 (430)	5300 (373)
N6	¼H	42500 (3000)	31300 (2200)	7825 (550)	This high magnesium alloy is not recommended for use in this temperature range.			

I.C.I. REFERENCE			I.C.I. REFERENCE	
SECTION	NUMBER	M.I.G. WELD DETAILS BUTT WELDS IN PLATES OF EQUAL THICKNESS FOR PLATES UP TO 1½" THICK.	SECTION	NUMBER
			PAGE	OF
DIV. REF. DRG.	I.C.I. REF. DRG.	SPECN:–	ISSUE No. DATE	
GENERAL REFERENCES				

PLATE THICKNESS OVER
·080" UP TO 3/16"

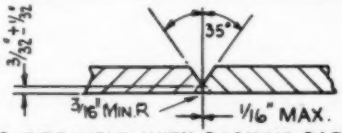
SINGLE SIDE WELD WITH BACKING BAR (FINE WIRE EQUIPMENT ONLY SHOULD BE USED ON THIS RANGE OF THK.)

PLATE THICKNESS OVER
3/16" UP TO 1/4"



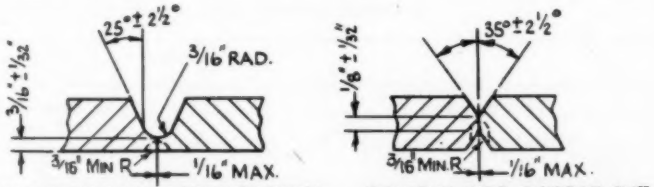
SINGLE SIDE WELD WITH BACKING BAR OR WELD FROM GROOVE SIDE, BACK CHIP AND SEAL WELD ROOT.

PLATE THICKNESS OVER
1/4" UP TO 3/8"



SINGLE SIDE WELD WITH BACKING BAR OR WELD FROM GROOVE SIDE, BACK CHIP AND SEAL WELD ROOT.

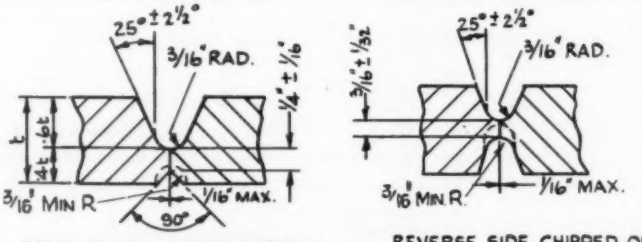
PLATE THICKNESS OVER
3/8" UP TO 3/4"



SINGLE SIDE WELD WITH BACKING BAR OR WELD FROM GROOVE SIDE, BACK CHIP AND SEAL WELD ROOT.

REVERSE SIDE CHIPPED OUT TO SOUND METAL BEFORE WELDING.

PLATE THICKNESS OVER
3/4" UP TO 1½"



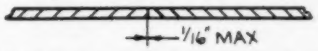
REVERSE SIDE CHIPPED OUT TO SOUND METAL BEFORE WELDING.

REVERSE SIDE CHIPPED OUT SOUND METAL BEFORE WELDING.

Typical Standard Sheet for Mig butt weld details in aluminium

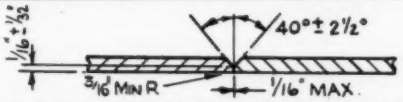
I.C.I. REFERENCE		T.I.G WELD DETAILS	I.C.I. REFERENCE	
SECTION	NUMBER	FOR ALUMINIUM & ALUMINIUM ALLOY VESSELS, PIPES & FLANGES.	SECTION	NUMBER
		BUTT WELDS IN PLATES OF EQUAL THICKNESS FOR PLATES UP TO 1½" THICK.	PAGE	OF
DIV. REF. DRG.	I.C.I. REF. DRG.	SPECN:-	ISSUE No. DATE	
GENERAL REFERENCES				

PLATE THICKNESS UP TO 1/8"



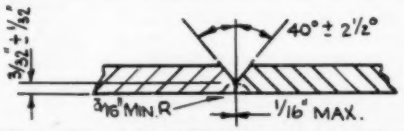
SINGLE SIDE WELD WITH BACKING BAR OR WELD FROM BOTH SIDES WITHOUT CHIPPING.

PLATE THICKNESS OVER 1/8" UP TO 1/4"



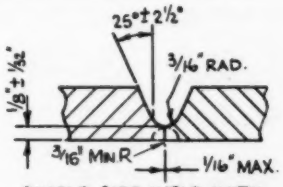
SINGLE SIDE WELD WITH BACKING BAR OR WELD FROM GROOVE SIDE, BACK CHIP AND SEAL WELD ROOT

PLATE THICKNESS OVER 1/4" UP TO 3/8"

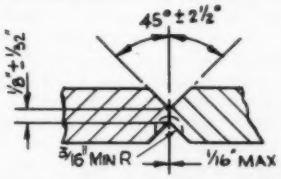


SINGLE SIDE WELD WITH BACKING BAR OR WELD FROM GROOVE SIDE, BACK CHIP AND SEAL WELD ROOT

PLATE THICKNESS OVER 3/8" UP TO 3/4"

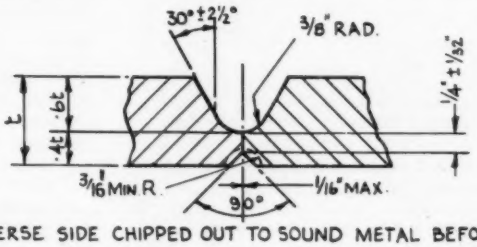


SINGLE SIDE WELD WITH BACKING BAR OR WELD FROM GROOVE SIDE, BACK CHIP & SEAL WELD ROOT.



REVERSE SIDE CHIPPED OUT TO SOUND METAL BEFORE WELDING.

PLATE THICKNESS OVER 3/4" UP TO 1½"



REVERSE SIDE CHIPPED OUT TO SOUND METAL BEFORE WELDING.

Typical Standard Sheet for Tig butt weld details in aluminium

stages of manufacture and the contractor shall give adequate notice when such stages are reached.

(i) After edge preparation when the shell plates are bent to circular form
(ii) When the domed ends are formed prior to attachment to the shell (See Part III, Clause 5)
(iii) When welding at the outside of any main seams has been completed and the 'second side' has been prepared for welding
(iv) When the surfaces of the butt welds are to be approved and the welds marked preparatory to radiographic examination (See Clause 5*a*)
(v) When the test plate attached to a longitudinal welded seam is ready for stamping for the identification of the individual test pieces prior to sub-division
(vi) When the openings have been prepared for branches, etc., and the parts assembled ready for welding
(vii) When the fabrication of the vessel is completed to check dimensional tolerances, circularity, etc.
(viii) When the pressure test is carried out
(ix) When the vessel has been dried out after the pressure test, the covers and blank mild steel discs fitted, and the vessel is ready for despatch
(x) Where it is indicated on the Company's drawing or order that additional inspections are required.

2. Testing Facilities

The Contractor shall supply free of charge the labour and appliances for such testing as may be carried out in accordance with the Specification.

The Contractor shall keep a record of all tests made as required by this Specification and shall forward copies to the Ordering Authority.

3. Provision of Test Plates Representing Welded Seams

(*a*) *Provision of Welded Test Plates*

(i) One test plate shall be provided at each end of each longitudinal seam above 6 ft (1·83 m) in length. For a longitudinal seam up to 6 ft 0 in. long, the set of test specimens shown in Fig.1* may be taken from a single test plate of sufficient length attached at one end of the seam.

Where the vessel is formed of several courses, the longitudinal seams in these courses shall for this purpose be regarded as one seam, provided that the courses are lined up for welding so that the total length of seam is welded in one continuous operation in each case.

(ii) The length of weld in the test plate shall be sufficient to provide material for tests required (Clause 3*b*), together with any re-tests which may be necessary (Clause 4*d*) and suitable allowances for discards and cutting (See Fig. 1).

(iii) The material used for the test plates shall be the same as that specified for the shell plates of the vessel and shall be of the same thickness as the shell plates represented.

The test plates shall be made of the following widths (See Fig. 1):

Thickness of vessel shell plate, in.	*Minimum width of each plate, in.*
Up to and including ¼ (6 mm)	6 (15 cm)
Over ¼ up to and including ½ (12 mm)	9 (23 cm)
Over ½ up to and including 1 (25 mm)	12 (30 cm)
Over 1 up to and including 2 (50 mm)	18 (46 cm)

(iv) The test plates shall be securely attached at the end of the seam to be welded and shall be suitably clamped or reinforced to prevent excessive distortion or warping (See BS.1500:1958, Part 1, Fig. 56). The weld in the test plate shall be made as an extension to the main seam weld, at the same time and with the same procedure as the main seam.

(v) Where there are circumferential seams only or where the method of welding the circumferential seams differs from that employed for the longitudinal seams, the method of providing the length of weld for test shall be agreed in writing between the Ordering Authority and the Contractor.

(vi) Where the surface of the weld is smooth and the reinforcement of suitable shape for radiography (See Clause 5) no dressing of the weld is required. If the weld reinforcement is of unsuitable shape or the weld surface uneven the weld in the test plate shall be dressed smooth (See Clause 5 and Part III Clause 9(i)).

(vii) Any straightening of a test plate that has warped during welding shall be carried out cold.

(viii) The test plate shall be subjected to radiographic examination in the same way as the main seams. The position of the individual test pieces required for the tests given in Clause 4 shall be selected and marked by the Company's Inspecting Engineer following his examination of the radiographs of the test plate. These positions shall be selected so as to avoid areas including flaws which would, in the main seams, normally require repairs.

Repairs of welds in test plates are not permitted unless agreement has been obtained from the Ordering Authority.

(*b*) *Details of Test Specimens*

Specimens are required for the following and shall be machined from the test plate provided:

One transverse tensile test (See Clause 4*a*)
One side bend test (See Clause 4*b*)
Macro-examinations (See Clause 4*c*).

4. Mechanical Test on Welded Plates

(*a*) *Transverse Tensile Test*

One transverse tensile test piece shall be prepared from the test plate; the dimensions of the specimen shall be in accordance with those shown in Fig. 2.

The weld in the test specimen shall be dressed smooth and flush with, but not below, the surface of the parent plate.

For materials up to and including N3, in Table 1 of Part II, the ultimate tensile strength shall be not less than the specified minimum U.T.S. in BS.1477 for the relevant material in the annealed condition. For N4, N5 and N5/6 material the acceptable U.T.S. for the weld shall be:

N4 —11·5 tons/sq.in. (1810 kg/sq.cm)
N5 —13·5 tons/sq.in. (2125 kg/sq.cm)
N5/6—16 tons/sq.in. (2520 kg/sq.cm).

(*b*) *Side Bend Tests*

One bend test specimen shall be cut transversely to the welded seam; the dimensions of this specimen shall be in accordance with those given in Fig. 3.

The weld shall be machined flush with, but not below, the surface of the parent material.

The diameter of the former round which the test specimens shall be bent shall not be more than 3 × width of the specimen for materials up to and including N3 in Table 3 of Part II, and 6 × width of specimen for N4, N5 and N5/6 materials and the test is to be continued until the two limbs are parallel.

On completion of the test no cracks or defects at the outer surface of the specimen shall be greater than 1/16th (1½ mm) measured across the specimen or 1/8th (3 mm) measured along the length of the specimen. The depth of any such defects shall not exceed 1/8 in.

(*c*) *Macro-Examination*

A specimen of the full section of the weld and covering a distance of 1 in. (25 mm) on each side of the weld shall be taken from each welded test plate for examination by the Company's Inspecting Engineer.

The Company reserve the right to etch and examine any other parts of the welded test plate, including the specimens removed for mechanical test, in order to ensure that the weld metal is free from contamination or that any contamination found in the test plate is local and is unlikely

*Figures for specification not included.

to be present in the welded seam or seams of the vessel itself.

(*d*) *Re-tests*

If any test fails to meet the above requirements, two re-tests of the same type as that which failed shall be taken from the same test plate and both of these shall comply with the above requirements. If one or both of these re-tests fail to comply with requirements, the Company reserve the right to reject the vessel represented by these tests or, alternatively at their discretion, to require complete rewelding of all the seams represented by such tests.

If required, test specimens after test shall be submitted for examination to the Division or Department of the Company which has issued the relevant order.

5. Radiography

(*a*) The surfaces and contour of the butt welded seams shall be examined by the Company's Inspecting Engineer for suitability for radiographic examination. Where the surfaces of the as-deposited butt welds are of unsuitable contour, or the reinforcement does not conform to Part III, Clause 9(i), the welds shall, on the instructions of the Company's Inspecting Engineer, be dressed by machining chipping or grinding. Grinding wheels used for this purpose shall be suitable for use with aluminium and shall not have been used on other metals or for other duties.

(*b*) X-ray radiographs shall be taken of the entire length of each butt welded seam both longitudinal and circumferential together with the seams in the corresponding test plates. Butt welds between the following parts shall also be radiographed:

(i) Branches of the type shown in Fig. 32.0 of BS.1500, to the shell
(ii) Weld neck flange to branch pipe
(iii) Weld neck flange to swaged-out branch
(iv) Branch pipe to swaged-out branch.

The radiographic technique shall be sufficiently sensitive to reveal a difference in metal thickness equal to 2% of the plate thickness, the sensitivity to be determined by the use of a penetrameter of the DIN-AL series placed on the weld. The density of that portion of the radiograph corresponding with the parent plate adjacent to the weld shall be not less than 2·0.

Radiographs shall be identified as specified in BS.1500: 1958, Part I, Section five (See Clause 3).

Any radiograph which fails to meet the requirements of the Company as regards radiographic quality shall be rejected and the length of welded seam represented by this radiograph shall again be radiographed.

The Contractor shall preserve full data concerning the radiographic technique and make this information available to the Company on request.

(*c*) All radiographs shall be submitted to the Company's Inspecting Engineer for examination in conjunction with his examination of the welded seam represented, no welding repairs having been carried out.

Radiographs shall show complete freedom from any of the following defects at any thickness of vessel plate:

(i) Cracks
(ii) Lack of fusion
(iii) Lack of penetration
(iv) Aligned porosity
(v) Tungsten inclusions greater than 10% in dia. of the thickness of material (with a maximum diameter of $\frac{1}{16}$ in. (1½ mm))
(vi) Oxide films greater than $\frac{1}{8}$ in. (3 mm) in length
(vii) Porosity of pore size greater than $\frac{1}{16}$ in. dia.

Tungsten inclusions

(*a*) Isolated inclusions up to $\frac{1}{16}$ in. dia. or 10% of the plate thickness, whichever is less, are not cause for rejection, provided that no two such particles are less than 1 in. apart and that there are not more than two in any 1 ft (30 cm) length of weld.

(*b*) Colonies of tungsten inclusions are not cause for rejection provided that:

(i) The particle size does not exceed $\frac{1}{32}$ in. diameter
(ii) The area bounded by the inclusions does not exceed $\frac{1}{4}$ in. diameter
(iii) The number of particles does not exceed five
(iv) No two colonies are less than 2 in. apart
(v) There are not more than two colonies in any 2 ft (60 cm) length of weld.

Oxide Films

Oxide films shall not be cause for rejection provided that they are randomly distributed, do not exceed $\frac{1}{8}$ in. in length, are at no time closer together than 2 in. and there are not more than two in any 2 ft length of weld.

Porosity

(*a*) The radiographs must indicate that the Contractor is consistently producing weld metal of the highest quality that can be achieved by first-class shop practice. Seams should, therefore, be substantially free from porosity, *e.g.*, as in those shown in B.W.R.A. booklet H3/58, "Classified Radiographs for Defects in Aluminium Welds", Figs. 2, 3, 5, 6 and 14. (Only porosity under consideration.)

(*b*) Provided that such overall high standard is achieved, porosity is acceptable in N4, N5 and N5/6 on the following basis in isolated 3 in. (76 mm) lengths of seam provided that the aggregate of such 3 in. lengths does not exceed 10% of the total length of the seam. For the various grades of aluminium (Alloy 1, 1A, 1B, and 1C) and N3 these acceptable porosity levels apply over the whole of the welded seam.

Maximum permissible frequency (per 3 in. length) of approximately spherical gas porosity in sheet and plate up to 0·75 in. thick.

Pore Size	*Sheet and Plate Thickness, in.* 0·2–0·3	0·3–0·5	0·5–0·75
Fine gas pores less than $\frac{1}{32}$ in. dia.	12	18	24
or Medium size gas pores $\frac{1}{32}$–$\frac{3}{64}$ in. dia.	6	8	10
or Large size gas pores $\frac{3}{64}$–$\frac{1}{16}$ in. dia.	—	4	4
Mixed pores	15	22	30

It is realised that isolated groups of porosity cannot be altogether eliminated at 'stops' and 'starts', especially when the Mig process is used, and that attempts to make good such defects by repair welding may, in fact, introduce more serious defects.

(*c*) Within the 10% aggregate length described, groups of pores are also acceptable in material over 0·3 in. thick provided that: Each group contains not more than five pores in an area not more than $\frac{1}{2}$ in. dia.; the groups are not less than 2 ft apart; and the pore size does not exceed $\frac{1}{32}$ in. dia. for material 0·3–0·5 in. thick and $\frac{3}{64}$ in. dia. for material over 0·5 in. thick (*e.g.*, faults as gross as B.W.R.A. Booklet H3/58, Fig. 19, are avoidable).

(*d*) Portions of welded seams not conforming to these requirements shall be cut out and rewelded using a welding technique which complies with the requirements of this Specification.

(*e*) On completion of repairs the rewelded portions shall again be radiographed by the techniques previously specified. The lead characters placed alongside each length of weld for identification purposes shall include the mark R.1 to indicate that repair welding has been carried out in the lengths of welded joint represented by the radiographs.

Any subsequent rapairs shall be identified by marks R.2, R.3. ..... indicating second, third, etc. repairs.

UTRECHT MEETING, 1961

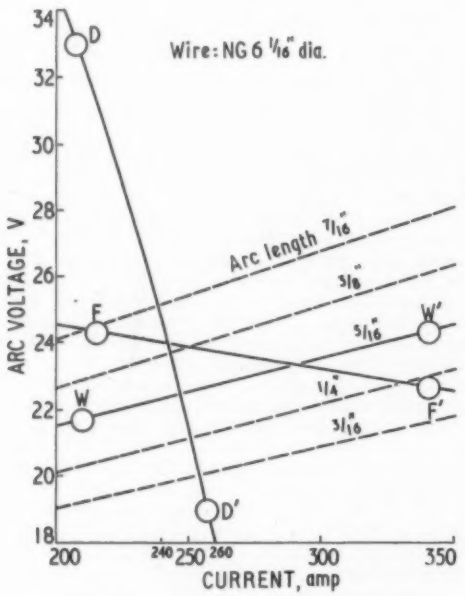
Development of Mig Welding Techniques for Aluminium

By J. E. Tomlinson, B.SC., A.I.M., *and D. Slater*, B.SC.

This paper reviews the development of inert-gas metal-arc welding equipment, practice and standards as applied to aluminium. Emphasis is laid on the fundamentals on which present techniques are based and attention is drawn to the value of scrupulous and thoughtful attention to a number of practical details.

Development of Equipment

IN THE Mig process as applied to aluminium, a d.c. arc is maintained between a mechanically fed consumable aluminium wire and the work, the weld area being shielded by a stream of inert-gas issuing from a nozzle surrounding the wire. In the early days of this process use was made of existing types of power sources, and many of the operational difficulties experienced, such as burn-backs and the tedious balancing of two or more controls when changing currents, can be attributed to their unsuitable characteristics. Today it is recognised that by the combination of particular electrode feed systems and power sources, 'single-knob' control of welding current is possible over a wide range without causing marked alteration in arc length.[1,2] Additionally, rapid self-adjustment of the arc is possible to combat variations in the distance between the welding gun and the work.



1—*Typical power source and arc characteristics*

Currently two combinations of feed system and power source are used. In the self-adjusting arc system the current is selected by the setting of the wire feed speed, and the power source must automatically supply the appropriate current at a pre-selected arc voltage (arc length). From the introduction of this process, manual Mig welding equipment for work on material over $\frac{1}{8}$ in. (3 mm) thick has almost invariably incorporated a wire feed arrangement appropriate to the self-adjusting arc system, and today almost all mechanised units also use this arrangement. The best type of power source can be determined from a consideration of arc characteristics. Each composition of electrode wire gives a characteristic linear rise of arc voltage with increasing current for an arc of constant length. Such characteristics for $\frac{1}{16}$ in. ($1\frac{1}{2}$ mm) dia. Al–5% Mg alloy wire in argon are plotted in Fig. 1, *WW'* being that for the typical visible arc length of $\frac{5}{16}$ in. (8 mm). If the current/voltage output characteristic of the power source is identical to *WW'*, any change in the wire feed speed will be accompanied by a change in the current output of the power source and a small change in the voltage of output such that the arc length remains unchanged. This degree of constancy is approached with the variable-slope power sources which are available today and which have up to 5 slopes selected by switching. So called 'flat-characteristic' sources usually show a drop of 1–2 volts per 100 amp welding current: represented by the line *FF'* in Fig. 1. With such a source, a change in wire feed speed to produce a current change from 240 to 260 amp causes a drop in arc voltage corresponding to a decrease in the arc length of less than $\frac{1}{16}$ in. Such a change is usually insignificant, and power sources of this type have, for some years, allowed 'single-knob' variations of welding current over wide ranges without

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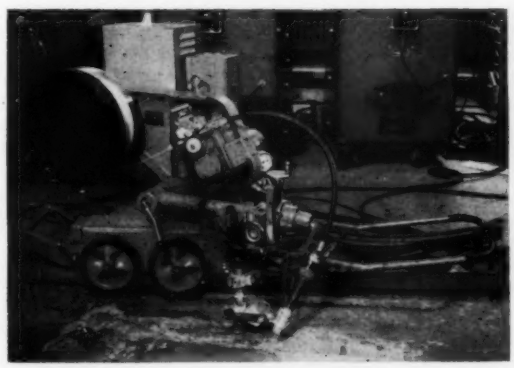
the need for alteration of the output voltage. Power sources of the constant current ('drooping characteristic') type, such as were commonly employed in the early days, do not allow single control of welding conditions for, as the characteristic DD' in Fig. 1 indicates, a change in wire feed speed to produce a change in current from 240 to 260 amp produces a decrease in the arc length of over $\frac{1}{4}$ in. ($6\frac{1}{3}$ mm), so that the arc will stub out. For this change in current to be made and a reasonable arc length maintained, alteration of both the wire feed speed and the power source controls is necessary. Recent British practice has favoured almost exclusively rectifiers of the flat characteristic type for use with self-adjusting arc systems. Some early models had the disadvantage that the open-circuit voltage (arc voltage) could not be altered under load, and a valued feature of contemporary sources is stepless control of voltage under load, preferably over the range 15–40 V.

In the alternative controlled-arc system the wire feed rate is made to depend on the arc voltage (arc length) that is pre-selected, and the power source should give little change in current with change in arc voltage; *i.e.*, it should have a 'drooping characteristic'. Most early mechanised equipment worked on this system. The Aircomatic Model C monitored the arc voltage, and the wire feed speed was varied appropriately by two motors, one a.c. operated and the other d.c. operated, acting through a differential, whereas the Sigma SWM.3 unit incorporated electronic control of the feed motor. A disadvantage of this system was the uncertainty, within certain ranges of operating conditions, of starting the arc because of the relatively low short-circuit current available from 'drooping characteristic' power sources. The controlled-arc system has recently reappeared in neater form in certain of the equipments produced for the welding of thin sheet, in which the feed motor is incorporated in the welding gun. In these units the wire feed rate is made to depend on the pre-selected arc voltage by driving the feed motor with a voltage proportional to that of the arc. Single-knob control of welding current is then obtained simply through variation of the current output of the power source. Rectifiers have been widely used with controlled-arc systems. Conventional 'drooping characteristic' motor generators have found less favour because of high noise and idling currents, change in output with running time and, possibly, inferior transient behaviour. However, a lightweight 'drooping characteristic' motor generator is proving to be a suitable, inexpensive source for the new guns for the welding of thin sheet, and which work on the controlled-arc system.

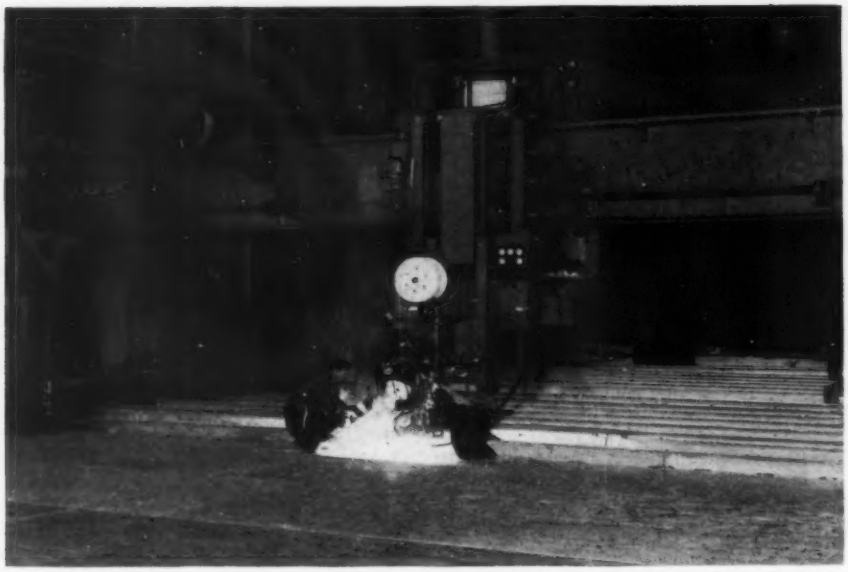
Manual welding equipments are either of the 'fine wire' type, feeding wires from 0·030 in. to $\frac{1}{16}$ in. (0·8–1·6 mm), in which the wire reel and drive are built into the gun, or the conventional type, feeding wires from $\frac{3}{64}$ in. to $\frac{3}{32}$ in. (1·2–2·4 mm) dia., in which the wire reel and drive are remote from the gun. The former are used on sheet metal work up to $\frac{1}{8}$–$\frac{3}{16}$ in. (3–5 mm) thick and for tacking large structures in thicker material. The conventional equipment is used for all other work on material $\frac{1}{8}$ in. thick and over. Important features of welding guns are the reliability and smoothness of the wire feed, the prevention of overrun of the wire when the trigger switch is released and, for guns with wire reels attached, the protection afforded to the reel against spatter. The weight of manual welding guns is a consideration but good balance is perhaps of even greater importance. In view of the higher cost of wire when wound on 1 lb ($\frac{1}{2}$ kg) reels, guns taking such reels are not used when the work can be done equally well by the heavier duty equipment with 10 lb ($4\frac{1}{2}$ kg) reels mounted on the control boxes, and nowadays considerable use is made of 30 lb ($13\frac{1}{2}$ kg) reels of wire on automatic equipment. Water cooling of welding guns is an encumbrance and unnecessary in all but the heaviest manual work. If water cooling has to be employed, a closed circuit system obviates long water hoses and has the advantage in cold climates that anti-freeze can be added. Portable controls of wire speed or current are useful in applications where the power sources are a considerable distance from the position of welding, and one gun has the advantage of an integral wire feed speed control. With reference to both manual and mechanised welding units, argon relays are often preferred to be in the control boxes rather than in the power sources so as to avoid excessive lengths of argon hose liable to air contamination. Provision for the purging of the argon system is also of value.

Over the past eight years, great advances have been made in the design of mechanised welding units for aluminium. Some have lightweight welding heads which may be very accurately positioned and are particularly suitable for a fixed installation under which relatively thin components are traversed or rotated. Others, of more rugged construction, are designed to be moved over the work either singly on a tractor (Fig. 2) or in pairs on a gantry (Fig. 3). The unit shown in Fig. 2 is interesting not only because it is self-guiding for fillet and some butt welding, but also because the welding head has a rise and fall motion which allows the welding of cambered panels. Desirable features of mechanised welding units are a rapid



2—*Prototype Q.A. self-guiding tractor-mounted Mig welding equipment*

means of roughly aligning the welding head, a drive motor as close to and as nearly in line with the welding head as possible, a barrel in the welding head giving the least turbulence in the argon stream, and a gas nozzle of good design and of a diameter appropriate to the width of weld being made.



3—General view of one of the two Q.A. Sigma-welding gantries at work on aluminium bulkhead sections for 'Canberra' super-structure

(Courtesy Harland & Wolff Ltd. and B.O.C. Ltd.)

Material Preparation

Forming

Few problems arise in the manipulation of aluminium and its alloys into shapes suitable for joining by welding provided that the fundamental principles governing the mechanical response of the alloys are thoroughly understood. Pure aluminium, although low in strength, possesses remarkably good ductility and can be formed by almost any method, including the most crude such as hammering and levering, with very little effect upon behaviour during welding. The increased strength of both the non-heat-treatable and heat-treatable alloys is gained at the expense of some of this ductility, and so they require more careful choice of forming method and must be formed over more generous radii. Hammering, levering, local bending, and such methods often give rise to excessive local deformation. This is particularly the case in hammering, where the surface is worked up to a much greater degree than the interior of the metal. Hence, even if the necessary force is available to form the harder alloys by hammering, there is a risk of the production of micro-fissures or incipient cracks where excessive local deformation is carried out. On the other hand, press-forming with accurately prepared tools helps to ensure that local over-straining is avoided. Forming operations give rise to residual stresses which tend to increase as the strength of the material increases. The stresses are relieved locally by the heat of welding and may introduce distortion which will be largely uncontrollable if a non-uniform method of forming, such as hammering, has been employed.

When dealing with the hot-short alloys, the magnitude of the cracking problem is primarily a function of the degree of restraint about a particular joint and is therefore a function of the stresses applied during cooling through the critical range. In such cases residual stresses inducing distortion may have a marked effect upon weldability and it may become desirable to anneal components which have been heavily worked where welding is to be carried out in the vicinity of the worked zones.

Edge preparation and cleaning—oxide removal

Whilst it has long since been shown that the fundamental problem in fusion welding aluminium is the removal of the tenacious superficial oxide film, it has taken time for the practical implications to be fully appreciated.

The need for thorough oxide removal, principally before welding but also between runs in multi-pass welding, can be summarised by considering the following factors:

(*a*) The presence of an oxide film on the surface of the joint will prevent fusion of the parts to be joined. This arises because aluminium oxide is refractory and remains as a solid film even though the underlying parent material is molten

(*b*) The naturally occurring oxide film is invariably hydrated and remains so even though preheat of the order of 200–300°C. is applied. The hydrated oxide only breaks down under the influence of the arc at temperatures in excess of about 1200°C. This dehydration releases water vapour which in turn dissociates to permit the solution of hydrogen in the molten aluminium. The solubility of hydrogen is very much greater in liquid aluminium than in the solid metal, and consequently hydrogen expelled as the metal freezes may be retained in the form of gas porosity

(*c*) Oxide film inclusions are likely to result in the weld metal where the surface oxide is inadequately removed before welding. Such inclusions may occur even where proper fusion is achieved.

The normal course of edge preparation and cleaning consists in producing the desired groove shape by some mechanical means and then removing surface contamination and the naturally occurring oxide film

as thoroughly as possible by an appropriate cleaning method. It is often found, however, that much of the cleaning procedure may be omitted if steps are taken to produce the desired groove form without introducing surface contamination.

Reference is made in some publications (*e.g.*, BS.3019) to the use of chemical methods for cleaning and removal of heavy oxide films, and process specifications exist in which chemical cleaning of the joint edge immediately before welding is mandatory. By a proper choice of pickling procedure, degreasing can be successfully accomplished together with satisfactory oxide film removal. This occurs when caustic soda cleaning is carried out but care should be taken to ensure that, in the neutralisation treatment which usually follows, the strength of the nitric acid solution should not be too high, otherwise some thickening of the oxide film may occur. Pickling treatments are really suitable only for simply shaped components or assemblies, for there is grave risk of water or pickling solution remaining entrapped in crevices existing in complex fabrications during the later stages of construction. Additionally, practical difficulties often limit the transportation of semi-fabricated assemblies from shop to shop, and as pickling or any other form of cleaning should be done with the minimum time elapsing between treatment and welding, some form of 'in-process' cleaning is generally necessary because the risk of re-contamination is normally very great in the average fabricating shop. There is apparently no published information on the relative efficacy of chemical and mechanical means of surface preparation cleaning but at present the latter are far more widely employed.

Mechanical means of cleaning should be considered in conjunction with the mechanical means of edge preparation. Provided that a machining method can be devised in which lubricant is unnecessary, an edge may be prepared suitable for welding without further treatment. High speed routing meets the requirements, and conditions can be set up ensuring the production of consistently good surfaces of low specific area. Manually operated routing cutters are tending to find some favour where chipping would normally be applied, but the degree of skill required in their use is greater than that required for chipping. Nevertheless, completely satisfactory surface preparation has been demonstrated by this method. Shaping or planing is widely used for edge preparation and properly executed it can give satisfactory results. However, for the best results lubrication is usually necessary and the edges then require degreasing. Grinding has been found to have little to commend it as a method of edge preparation and where possible it should be avoided. The surface produced by grinding consists of an extensively disturbed layer in which there is intimately mixed a high proportion of broken hydrated oxide and contaminating matter from the grinding operation. The hydrated oxide is a possible source of hydrogen porosity, and wetting of the surface and good fusion are likely to be inhibited. Rotary files, routers, and similar tools may usually be adapted for use where access to the joint is obstructed by adjacent parts. Chipping is generally preferred to grinding as a method of edge preparation in places not accessible for machining. When skilfully executed with chisels in good order a relatively smooth surface may be achieved. When badly carried out, however, using blunt, poorly shaped chisels, a quite unsatisfactory surface may result. Contamination of the surface irregularities readily occurs and arc scavenging is made more difficult by the presence of asperities. Rough chipping followed by final smoothing is to be preferred.

For the cleaning of surfaces other than those involved in edge preparation, power scratch brushing is the most widely practised method both for mechanised welding for quantity production and for the manual welding of general engineering and marine structures. In work of the highest quality, possibly the best method for edge cleaning immediately before welding is that using hard steel scrapers. There is a strong feeling that in such high class work the job of edge cleaning before welding should be the responsibility of the welder and, by constructing his own scraping tools, and by using a method such as scraping where satisfactory execution is clearly demonstrated by visual inspection only, a due sense of responsibility may be imparted. An additional advantage of such a procedure is that the risk of contamination between cleaning and welding is very slight, as a welder need prepare only such surfaces as he can comfortably weld at a given time. This method of cleaning may be employed at any stage during fabrication, even on the most complex assemblies.

No matter what cleaning method is employed, there is a limiting thickness of oxide film present on the work immediately before welding, and it is only that inevitably occurring film that should be present for removal by arc action. It is established that where oxide is encountered that remains solid when the underlying metal becomes molten, successful cleaning of the surface in the chemical sense can be achieved, other than by chemical fluxing, only when the arc is used with the work piece negative and the electrode positive.[3] Under these conditions the oxide is partly mechanically removed by the bombardment of ions from the electrode and partly physically dissociated, providing electrons which travel from the work piece to the positive electrode, thus contributing to the arc current. In the conventional Mig welding of aluminium, metal is transferred across the arc in the form of a fine spray and it is inevitable that a small proportion of this spray near the outer fringes of the arc cone becomes partly oxidised. This is particularly noticeable when using Al–Mg alloy electrode wire. The partly oxidised material is deposited all round the arc and results in the appearance of a broad band of black 'smut' on either side of the weld bead. Smut deposited behind the arc falls on the weld pool and tends to coalesce to form an elongated stringer of oxide scum. That deposited ahead of the arc is partly consumed by arc action and dissociation, while a small amount remaining tends to coalesce on the surface of the weld pool as this advances, to add to the scum stringers. Consequently when Al–Mg alloy electrode wire is used, particular attention is paid to the removal of heavy oxide films from the welding groove, for removal by arc action is limited through the deposition of smut ahead of the arc.

It is easy to visualise an arc running at a given current possessing a certain oxide scavenging power and it follows that any reduction in total surface which

the arc is required to clean will be advantageous. Smooth surfaces, such as those produced by high-speed routing, will give less risk of the inclusion of oxide and of poor fusion than dragged surfaces produced by rough machining. The high specific surface produced by excessively heavy scratch brushing is a less widely appreciated source of trouble.

It will be appreciated that, in high quality work, the execution of specific cleaning procedures will account for a significant part of the cost of fabrication. In the interest of economy it is necessary to ensure that, although cleaning should be scrupulously carried out where required, unnecessary cleaning should be avoided. It is a common sight to see broad bands of metal on either side of the weld joint laboriously cleaned by wire brushing, scraping, or chemical means. The treatment of these broad bands in no way influences the ultimate quality of the welded joint and it is quite unnecessary to clean more than about $\frac{1}{8}$ in. (3 mm) beyond the expected limit of the weld. In practice it is difficult to be as precise as this and it is reasonable to specify for cleaning a band $\frac{1}{4}$–$\frac{3}{8}$ in. ($6\frac{1}{2}$–$9\frac{1}{2}$ mm) wide measured from the edge of the groove in addition to the groove faces themselves if they have become contaminated since preparation. Whilst the whole of the cleaned area should be treated to a high standard it is found that particular attention must be paid to abutting root faces, for they are often unexposed to the action of the arc. Any oxide present on these surfaces will normally be dispersed through the weld metal, though should a thick film be present serious oxide film inclusions may result.

Controversy has existed in the past concerning the relative merits of chemical and mechanical methods of electrode wire cleaning. Mechanically scraped electrode wire has been produced in North America and it is claimed that its use has resulted in a reduction of porosity arising from surface contamination of the wire by the wire drawing process. In Britain reliance is placed on chemical cleaning methods and careful packaging. Comparative tests carried out in Britain appear to show no significant difference in the results obtained with either form of wire, particularly with respect to porosity, an acceptable standard being obtainable in either case provided that a satisfactory welding procedure is adopted.

Shielding Gases

Many claims have been made concerning the improved quality obtainable when aluminium welds are made by the Mig process using gases and gas mixtures other than pure argon. Helium and argon–helium mixtures are used in the U.S.A. for example,[4] and small additions of chlorine to argon have been proposed.[5] Reports of satisfactory tests using small quantities of oxygen added to argon[6] would indicate that this approach might be worth further consideration for the welding of pure aluminium, though it is likely to be unsuitable for alloys containing appreciable quantities of magnesium. The use of chlorine additions to argon presents a considerable problem not only from the health and safety aspect but also metallurgically in the selection of materials for construction of the welding apparatus and in the possible risk of corrosion if aluminium chloride is deposited on the weldment. Nevertheless, chlorine has been used in the aluminium foundry for a considerable time as a gaseous flux. Helium is not available in Europe as a commercially practicable shielding gas but from a theoretical viewpoint has an attraction in that a given arc may be run at a higher voltage using helium–argon mixtures with a consequently greater heat input, flatter weld bead, and a more favourably shaped solidification front allowing hydrogen to escape rather than become entrapped between solidifying dendrites. There is little practical experience in Britain in the use of helium and, despite the technical claims for these gas mixtures, it is true to say that radiographic quality better than that demanded by the A.S.M.E. Code can be achieved using pure argon, provided that a thorough grasp is made of the mechanism by which porosity occurs. By careful attention to cleaning methods, eliminating all avoidable sources of hydrogen pick-up, a low hydrogen content in the molten weld pool may be achieved. From then on, it is a matter of ensuring the slowest practicable freezing rate so as to allow such hydrogen bubbles as are formed to escape from the weld pool. It is common experience that this is more difficult to achieve in materials such as pure aluminium, which has a short freezing range, than in the Al–5% Mg alloy for example.

Joint Configurations

Edge preparation for butt joints

The forms of butt joint currently used in most British Mig welding applications are typified in Table I. It seems generally agreed that with temporarily backed close joints, edge preparation is unnecessary on metal up to $\frac{1}{8}$ in. (3 mm) thick and that, if an open joint is to be made with a stiffener to provide permanent backing, edge preparation is unnecessary on material up to $\frac{5}{16}$ in. (8 mm) thick. With the Mig process any alteration in the welding conditions to increase penetration will produce an almost proportionate increase in the amount of electrode metal deposited, so that attempts to make close square butt joints in thick material invariably produce welds with excessive reinforcement. The depth and angles of bevels for plate edges are selected in relation to the penetration required, to minimise the entrapment of spatter and to ensure good side wall fusion. Early attempts to use steepsided grooves when welding thick aluminium plate often gave rise to side wall defects and it was only when more generous angles were employed, thus reducing the effective heat sink, that consistently satisfactory fusion was achieved. Thus, it is uncommon in manual welding to find included groove angles specified less than 50°, even when welding very heavy plate, whereas in steel welding 20° or even less may be encountered in heavy fabrication. In mechanised welding, where higher currents may be employed, narrower angle grooves are sometimes found in plates about 1 in. thick but it must be remembered that in this case the relative size of weld bead to plate is about the same as that when welding plate of half that thickness by manual methods. Wide groove angles still appear to be necessary when welding very heavy plate by mechanised means though there is

Table Ia—Butt joint configurations—Type 1 (A and B)—close square butt

Applications

Type 1A is used for most butts in metal up to $\frac{1}{8}$ in. thick. On thicker metal it is recommended for jigged, mechanised butt welding only and is useful for joining metal panels up to $\frac{1}{4}$ in. thick where excessive reinforcement is not objectionable.

Type 1B, welded from both sides can be used for the automatic welding of seams in large tanks, but requires strict control of conditions to ensure adequate inter-penetration. If back chipping cannot be employed this joint should only be used for manual welding in low-stressed applications where full strength efficiency has not to be guaranteed, because of the difficulty of ensuring adequate inter-penetration.

Assets

(1) No edge preparation other than $\frac{1}{16}$ in. sighting V filed on edges.
(2) No back chipping with mechanical welding.
(3) With type 2B no backing is needed and whilst jigging gives best results, tacking, preferably on the opposite side to that first welded, can be employed.

NOTES

Reinforcement is heavy on one side in the case of 1A and on both sides in the case of 1B.

Remarks	A	B
Thickness	$\frac{1}{16}$–$\frac{3}{16}$ in. manually $\frac{3}{16}$–$\frac{1}{4}$ in. mechanical traverse	$\frac{3}{16}$–$\frac{3}{8}$ in. manually $\frac{1}{4}$–$\frac{1}{2}$ in. mechanical traverse
Root Gap	Nil	Nil
Backing Bar	Temporary grooved steel or aluminium	Nil
Gun	Manual or mechanical traverse	
No. of Passes	One	One from each side
Position	Flat	Flat
Back Chipping	Not required	Recommended for manual work. Not required for mechanical traverse

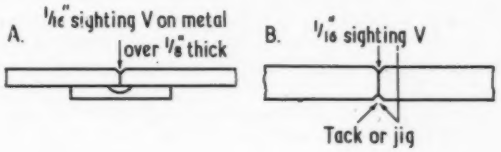


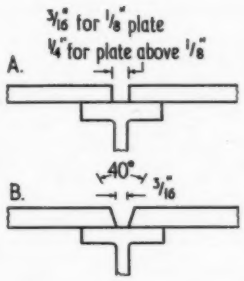
Table Ib—Butt joint configurations—Type 2 (A and B)—open square backed butt

Applications

Primarily for shipbuilding and other structures, built of stiffened panels.

Assets

(1) Minimum edge preparation
(2) Tolerant of variations in fit-up and welding conditions.
(3) Self-jigging: useful either for one-off or limited production with manual operation or for large-scale production with mechanical traverse.
(4) Strength relatively insensitive to porosity if associated lap welds to backing are completed.
(5) Gives flush finish on top side with little fettling.



Remarks	A	B
Thickness	Downhand: $\frac{1}{8}$–$\frac{1}{16}$ in. Other positions: $\frac{1}{8}$–$\frac{3}{16}$ in.	$\frac{3}{8}$ in. upwards $\frac{3}{16}$ in. upwards
Backing Bar	Permanent aluminium backing for extruded section double fillet welded to plate	
Gun	Manual or mechanical traverse	
Position	All (see Thickness)	
Back Chipping	Not required	

Table Ic—Butt joint configurations—Type 3 (A and B)—single Y butt

Applications

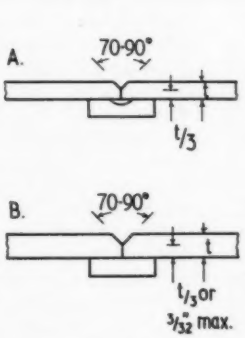
Good quality butts made away from stiffeners, *e.g.*, for tanks, containers and boat hulls

Assets

(1) Edge preparation simple. Can be done by sawing, grinding, planing, or tungsten-arc cutting
(2) Suitable for radiographic examination
(3) Gives flush surface on top side with little fettling

NOTES

Underbead from type 3A should be removed to develop best mechanical properties



Remarks	A	B
Thickness	$\frac{3}{16}$–$\frac{1}{2}$ in.	$\frac{1}{4}$–$\frac{1}{2}$ in.
Root Gap	Nil	Nil
Backing Bar	Temporary grooved steel or aluminium	Temporary flat aluminium backing optional
Gun	Manual or mechanical traverse	
No. of Passes	One from one side	One or more from both sides
Position	Flat only	All
Back Chipping	Not required	Recommended after first pass

Table Id—Butt joint configurations—Type 4—single U butt

Applications

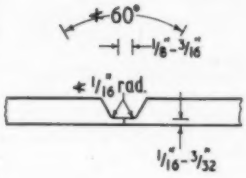
For butts in piping and highest quality positional butts in tanks, containers, etc.

Assets

(1) Easier control of penetration than with type 3
(2) Suitable for radiographic examination
(3) Gives flush surface on top side with little fettling

NOTES

(1) Demands planing or milling machine for preparation
(2) More expensive to prepare than type 3 and joint requires more weld metal



Remarks

Thickness	Pipes $\frac{3}{16}$–$\frac{3}{4}$ in. Plates $\frac{1}{4}$–$\frac{3}{4}$ in.
Root Gap	Nil
Backing Bar	Temporary, grooved steel or aluminium
Gun	Manual or mechanical traverse
No. of Passes	One or more passes from one side depending on thickness
Position	All
Back Chipping	Not required

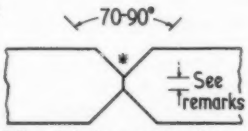
Table Ie—Butt joint configurations—Type 5—double V butt

Applications

Butt made away from stiffeners in plate $\frac{1}{4}$ in. thick and over for shipbuilding and tank work

Assets

(1) Preparation can be done by sawing, grinding, planing and tungsten-arc cutting
(2) Suitable for radiographic examination
(3) Gives flush surfaces with little fettling
(4) Relatively well balanced weld giving little distortion



*To minimise angular distortion, grooves may be made of unequal depth, as in the welding of steel.

Remarks

Thickness	$\frac{1}{4}$ in. upwards
Root Gap	Nil–$\frac{1}{16}$ in.
Nose	$\frac{3}{32}$ in. max. for manual work, $\frac{1}{16}$ in. for high-current mechanical welding
Backing Bar	Not required
Gun	Manual or mechanical traverse
No. of Passes	One or more from each side depending on thickness and position
Position	Manual: All Mechanical traverse: Flat only
Back Chipping	Required after first pass

Table If—Butt joint configurations—Type 6—double U butt

Applications

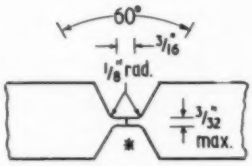
High quality butts in plate over $\frac{1}{4}$ in. thick

Assets

(1) Less susceptible to lack of fusion along centre-line and easier to back chip than type 5
(2) Suitable for radiographic examination
(3) Gives flush surfaces with little fettling
(4) Relatively well balanced weld giving little distortion

NOTES

(1) Demands planing or milling machine for preparation
(2) More expensive to prepare than type 5 and joint requires more weld metal



*To minimise angular distortion, grooves may be made of unequal depth, as in the welding of steel.

Remarks

Thickness	$\frac{1}{4}$ in. upwards
Root Gap	Nil–$\frac{1}{16}$ in.
Backing Bar	Not required
Gun	Manual
No. of Passes	One or more from each side depending on thickness and position
Position	Manual: Flat, vertical and overhead (Type 5 recommended for horizontal/vertical)
Back Chipping	Required

insufficient experience to formulate general recommendations.

Lack of fusion at the nose of joints welded from both sides was a rather troublesome defect in the early days of this process, but in manual welding limitation of the nose depth to a maximum of $\frac{3}{32}$ in. (2·4 mm), coupled sometimes with the employment of a slight gap and proper control of the back chipping operation, have enabled this problem to be overcome.

Configurations and techniques for other forms of joint

T joints can be made with single pass fillets with leg lengths from $\frac{3}{32}$ in. (2·4 mm) using 0·030 in. (0·8 mm) dia. wire to $\frac{3}{8}$ in. (9·5 mm) in the horizontal-vertical position and $\frac{1}{4}$ in. (6·4 mm) in the vertical and overhead positions using $\frac{3}{32}$ in. dia. wire in the former case and $\frac{1}{16}$ in. (1$\frac{1}{2}$ mm) for the latter. Where full root penetration is required, welding is done in the inclined or horizontal-vertical positions whenever possible and members thicker than $\frac{1}{4}$ in. are bevelled on each edge at an angle of 45° to leave a root face of $\frac{1}{16}$ in.

Corner joints in metal from $\frac{1}{16}$ in., $\frac{1}{2}$ (12·7 mm) and $\frac{1}{8}$ in. are usually made by the Tig process though the 'fine wire' Mig guns may be used. Corner joints in metal thicker than $\frac{1}{8}$ in. are made with conventional equipment employing either temporary backing or a small overlap. Lap joints are considered possible in all positions in metal from $\frac{1}{16}$ in. upwards. The Tig process is preferred for edge joints in material up to $\frac{1}{8}$ in. thick. On thicker metal, edge joints are made with a butt weld using a V preparation.

Welding Procedure

Selection of welding current

Data have been published showing the influence of plate thickness on penetration achieved at various welding currents, indicating the degree of fusion expected.[7] The essential factor to bear in mind is that, as aluminium and its alloys have a high thermal conductivity, an appreciably greater heat input is required to achieve the same extent of fusion when welding thick plate as compared with thin plate. Additional heat input is obtained by increasing the welding current, but adopting this simple expedient introduces a number of complications. Since the arc is maintained between a consumable electrode and the work, an increase in welding current will be accompanied by a proportionate increase in the amount of electrode material deposited in a given time.[3,8] Hence, if the welding speed is kept constant the extra deposited metal will either form a more upstanding weld bead or will overlap the surface, depending upon the magnitude of the heat sink. In the latter case an even greater heat input is required to provide adequate fusion with the parent plate, and the only way to prevent the cycle beginning once again is to alter the joint configuration. In other cases an increase in speed may well overcome the disadvantages of excess metal deposition, for it is found that whereas penetration (fusion) is more profoundly affected by welding current than by travel speed, bead size is more significantly affected by travel speed.[7] Unfortunately the extent to which the welding current can be increased is limited by the instability of the arc (puckering)[9] which is encountered at current levels between 350–600 amp, the precise level at which it occurs being dependent, among other things, upon travel speed,[7] joint configuration, and the design of the welding head. The exact choice of conditions when operating in this borderline region appears to be a matter for judicious experimentation on the shop floor.

Selection of wire diameter

Smith and Poley[8] have demonstrated the current range in which spray type transfer may be obtained with different wire diameters, illustrating for example, that usable currents may lie between 100 and 300 amp when $\frac{3}{64}$ in. (1·2 mm) dia. electrode wire is used. In practice it is often found convenient to decide on a particular current for a given wire diameter within the ranges shown by Smith and Poley. Thus 0·030 in. (0·8 mm) dia. wire is found to function well at about 110 amp, $\frac{3}{64}$ in. (1·2 mm) at a 180 amp, $\frac{1}{16}$ in. (1·6 mm) at 230 amp, and $\frac{3}{32}$ in. (2·4 mm) at 350 amp. This applies particularly to manual welding where, above all, it is essential that the running of the arc and deposition of metal should be as smooth and controllable as possible. Currents greater than 350 amp are generally impracticable using manual techniques, hence plates more than about $\frac{3}{8}$ in. ($9\frac{1}{2}$ mm) thick must be welded by multiple passes if this is to be done manually.[7] The downhand welding of such material is usually done with $\frac{3}{32}$ in. wire but for positional work there is a definite preference for $\frac{1}{16}$ in. dia. wire because at identical currents the weld pool is more easily controlled. For many applications therefore, welding conditions can be simplified so that one or possibly two currents are standardised for each size of electrode wire, and Table II gives typical examples.

Table II

Simplified selection of manual Mig welding conditions

Electrode Wire Dia. in. (mm)	*Welding Current, amp*	*Range of Metal Thickness, in. (mm)*	*Applications: Welding Position*
0·030 (0·8)	80	16–14 s.w.g. (1·6–2)	All
	110	13–10 s.w.g. (2·4–3·2)	All
$\frac{3}{64}$ (1·2)	180	$\frac{1}{8}$–$\frac{3}{16}$ (3–5)	All
$\frac{1}{16}$ (1·6)	230	$\frac{1}{4}$–$\frac{1}{2}$ (6–13)	All
	260	$\frac{1}{4}$ upwards	Positional work
$\frac{3}{32}$ (2·4)	350	$\frac{3}{8}$ upwards (9·5)	Downhand work

In most cases it is found that variation in the speed of welding will adequately compensate for the effects of thickness variation within the stated ranges and whilst, for example, much work between 14 s.w.g. and $\frac{3}{8}$ in. thickness could be carried out using $\frac{3}{64}$ in. dia. wire by varying the welding current, the preservation of constant arc conditions by a fixed welding current in terms of wire diameter is often of considerable practicable benefit to the operator.

Technique

Manual welding is almost invariably carried out in the leftwards direction with the welding gun inclined 10–15° from the vertical in the direction of travel. It is a widely accepted view that porosity is minimised by ensuring that the arc length is from $\frac{1}{4}$–$\frac{5}{16}$ in. long, and this is the working rule except in the welding of material thinner than $\frac{1}{8}$ in., where shorter arcs are necessary to allow adequate control over weld shape.[10] 'Dip-transfer' conditions, so valuable for the welding of thin gauge mild and stainless steel, seem to offer less advantage for the welding of thin aluminium. The control of penetration and gap-bridging properties are not reproduced to the same extent.

While lack of fusion and oxide or spatter entrapment are to some extent controlled by joint configuration, the skill of the welder can exert a significant influence. Trouble of this kind often occurs when the welder does not maintain the correct gun angles throughout a run. Movement from the wrists rather than from the waist and failure to rotate the gun so that it is always approximately normal to the fusion faces during weaving have been traced as sources of these defects.

Equipment and maintenance

Once the best welding conditions have been selected for a particular application, the main problem in achieving consistently satisfactory results becomes one of equipment reliability, and this generally resolves itself about difficulties arising from the wire feed mechanism. It is particularly frustrating for a welder to be constantly stopping to replace burnt contact tubes and having laboriously to remove the aluminium–copper alloy deposited in the groove when a wire stoppage occurs. Early equipments for manual welding, embodying drooping-characteristic power sources but still relying on arc self-adjustment for maintenance of the welding conditions, were particularly liable to burn-back trouble, for the open-circuit voltage of the

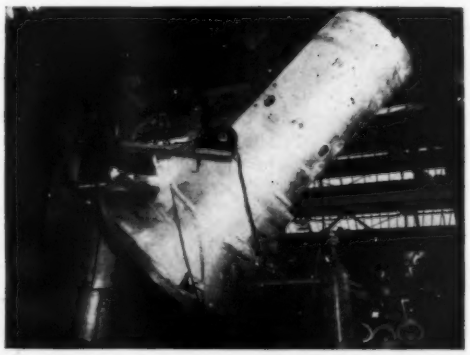
power source was usually high enough to allow a long arc to be maintained between the contact tube and the work if wire stoppage occurred. Today, using constant-potential power sources, it is often found that the arc is extinguished at the point in the cycle when a molten blob of aluminium is formed at the end of the stopped wire just as it emerges from the contact tube. Repair or replacement of the tube is often unnecessary where the contact tube itself is not associated with the cause of wire stoppage.

Developments in the design of wire driving wheels have played an important part in overcoming wire stoppage difficulties. The semi-circular type of groove found on early wire drive units has proved to be particularly unreliable when used with electrode wire of varying temper and staightness. Wire kinks, which may only be detected by careful visual examination along the length of the electrode wire, may be sufficient to cause feeding troubles, and any tendency towards wedging between the spool flanges and successive layers will certainly promote difficulty. The combination of V- and flat roll used on recent equipment appears to be significantly better in coping with the variations in wire quality which may be encountered. It is obvious that every effort must be made to reduce friction in the wire transporting system, and in general the least trouble will be experienced where the distance between the drive rolls and the arc is as short as possible. This consideration led to the development of the so-called 'fine-wire' welding equipment, in which the drive motor and wheels are situated in the gun close to the arc, but this design is necessarily limited to lightweight units and as a consequence the heavy motors required to pull $\frac{1}{16}$ in. or $\frac{3}{32}$ in. dia. electrode wires through several feet of flexible conduit cannot be accommodated. The 'wire pushing' manual equipment may often be advantageously modified by reducing the length of flexible conduit to the minimum required for a specific application, especially with $\frac{3}{64}$ in. dia. wire where much shop work has been done with conduits reduced to about 4 ft (1·23 m) long. It is an elementary precaution to ensure not only that nylon liners are of the correct diameter for the wire being used but that they are also of the correct length to ensure a continuous nylon tube between the drive wheels and the contact tube. Failure to do this will almost certainly result in wire snagging. Another simple but essential precaution is to ensure that, where the fused end of a contact tube is sawn off, burrs are removed from the bore. Following a burn-back, it is also important to run out the whole length of electrode wire between the driving rolls and the contact tube, for this length of wire may have been buckled slightly by the over-run of the drive motor when the burn-back occurred.

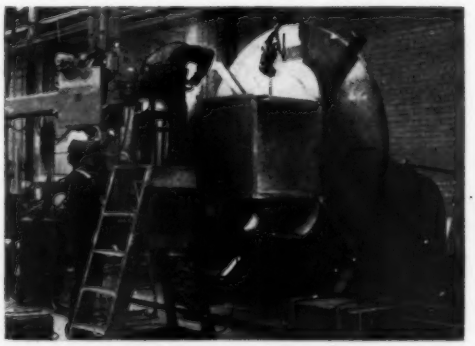
Periodic examination of the flowmeter and all joints in the argon tubing has been found beneficial in maintaining high weld quality, and if equipment has not been used for some hours it has been found advisable to purge the argon system.

Welding position

One of the outstanding characteristics of the Mig process is the facility with which positional welding may be carried out. Aluminium is a light metal having a high thermal conductivity with a tendency towards the formation of smaller weld pools than is the case when welding steel. The effects of gravity are much less pronounced and it has been found that a reduction in current by about 20% compared with that for downhand welding is all that is necessary to ensure successful vertical or overhead welding. For the highest quality work, however, there is some advantage in executing as much of the work as possible in the downhand position, for the risk of weld porosity is thus minimised. It may be imagined that elaborate manipulation equipment would be required to ensure that this could be done when working on complex fabrications but in practice it is found that a little ingenuity generally suffices. Figure 4 shows welding being carried out in one of the authors' Works on the core tank for a Merlin 'swimming pool' type reactor. The natural welding position for this seam would have been semi-inclined but it was considered worthwhile to use a crane and a simple set of rollers to sling the vessel for downhand welding. This procedure was amply justified in that no repairs were required following radiography of this difficult seam. Figure 5 shows the extent to which shop floor ingenuity may go in ensuring that the welder may adopt the most comfortable position for welding a heavy corner joint, again on a nuclear reactor core tank constructed in one of the authors' Works. This and seven other similar difficult joints were welded without the need for repair work following radiography, as a result of



4—Core tank for Merlin reactor under construction for A.E.I.–John Thompson, arranged for downhand welding



5—Semi-automatic welding of heavy box section corner joints

careful forethought based on hard lessons learned in the past.

Mechanised Mig welding

Because the electrode feed and welding current are readily pre-set and made interdependent, the Mig process is particularly amenable to mechanised operation. Full advantage can be taken of the high welding speed possible with this process, so high outputs can be obtained without operator fatigue, and distortion and the softening of heat-treatable or work-hardened products can be reduced. On thick material, heavier currents can be used and heavier deposits laid than by manual means. On thin material larger electrode wires can be used with higher welding speeds than are possible with manual welding.

Mechanised operation shows to great advantage in fillet welding, for the control of fillet size (which is a source of considerable variation in the strength and cost of manually laid welds) can readily be brought under strict control. If the electrode wire feed speed and speed of traverse of the welding head, or the work, are set, the welds will be of correct size. The welding current can be regarded simply as a means of burning off the electrode wire, and the pre-set arc voltage together with the inclination of the welding head as controlling the shape of the fillet. In the mechanised fillet and lap welding of metal thinner than $\frac{3}{16}$ in., good fit-up of the components and accurate alignment of the welding head have been found vital if neat, regular welds are to be produced. Particularly on small or rotated components, the welding speed should be as high as possible to minimise heating of the work and consequent changes in the shape and size of the weld from start to finish. For successful high speed fillet welding it has been found necessary to use an arc length somewhat shorter than usual (the voltage should be less than 23 V), otherwise at speeds over 40 in./min (100 cm/min), there will be a risk of intermittent lack of side and root fusion leading to the production of 'holes'.

Standards of Weld Quality

A great deal has been said and published concerning the controversial topic of aluminium weld quality and standards of acceptance, and much of this comment has undoubtedly arisen from the unfortunate fact that a certain amount of weld metal porosity is virtually unavoidable in most fabrications made using the Mig process. Furthermore, the complete exclusion of aluminium oxide from the weld presents a difficult problem because the densities of aluminium and its oxides are closely similar. There is little doubt that weld quality has generally improved over the past ten years but, as experience has been gained, more difficult and diverse fabrications have been attempted and occasional set-backs encountered, usually as old problems arise from new or aggravated causes. It is not intended in this paper to deal exhaustively with this topic but it is felt useful to set out the differing acceptance standards which have been applied over the past five years. A consideration of these standards and the allied mechanical test figures will show that there is wide scope for rationalisation and, whilst the application of a particular standard may be conditioned by a large factor of ignorance in specific cases, the widely divergent views held concerning the significance of defects must be noted with some scepticism.

Three standards are considered:

Standard 1: Applied to pressure vessels in pure aluminium (99·5% aluminium, BS.1477 P1B). Date: 1956.

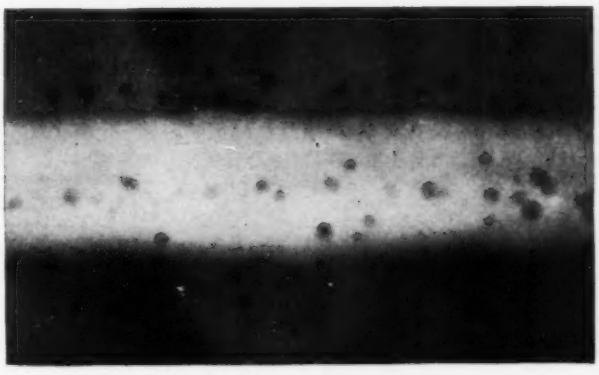
1. Cracks: Not acceptable.
2. Lack of fusion: Not acceptable.
3. Oxide film inclusions: Acceptable up to $\frac{3}{8}$ in. (9½ mm) dia. or length spaced at intervals of not less than 10 times the weld width.
4. Tungsten inclusions: Acceptable up to $\frac{1}{16}$ in. (1½ mm) dia.
5. Distributed porosity: Acceptable where the individual pore diameter does not exceed one-eighth of the plate thickness, *i.e.*, ½ in. (3 mm) dia. for 1 in. (25 mm) plate, etc. (Distribution not specified but Fig. 6 is typical of the standard accepted and which in fact showed 100% joint efficiency.)

Standard 2: Applied to vessels for low-temperature work where leakage would be dangerous. Aluminium–4½% magnesium alloy, BS.1477, NP5/6. Date: 1958.

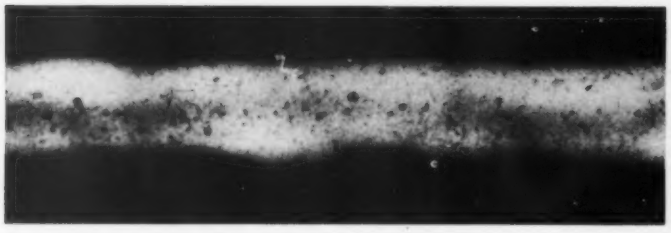
1. Cracks: Unacceptable.
2. Lack of fusion: Unacceptable.
3. Oxide films: Acceptable up to ¼ in. (6½ mm) long.
4. Scattered fine porosity: Acceptable up to $\frac{1}{16}$ in. dia. with local porosity up to $\frac{3}{32}$ in. (2½ mm) dia. (Distribution unspecified but Fig. 7 is typical of the quality accepted. Again 100% joint efficiency related to minimum specified strength for annealed plate was achieved.)

Standard 3: Applied to nuclear work in pure aluminium. Date: 1960.

1. Cracks: Unacceptable.
2. Lack of fusion: Unacceptable.
3. Lack of penetration: Unacceptable.
4. Not more than two pores of $\frac{1}{16}$ in. dia. may exist in any one length of 6 in. (152 mm) of weld and these must be separated by at least ¼ in.



6—Standard 1: Acceptable porosity in 1 in. (25 mm) thick 99·5% pure aluminium. Tensile strength of joint 5·0 tons/sq.in. (800 kg/sq.cm)



7—*Standard 2: Acceptable porosity in ½ in. (16 mm) thick Al–4½% Mg alloy. Tensile strength of joint 17·5 tons/sq.in. (2800 kg/sq.cm)*

8—*Lack of fusion not detected by radiography. 1⅜ in. (35 mm) thick Al–4½ Mg alloy. Tensile strength 13·3 tons/sq.in. (2100 kg/sq.cm) (78% joint efficiency). Bend testing could have missed this defect had it been discontinuous*

5. Restart porosity: May be permitted provided that the group consists of no more than six pores of individual diameter $\frac{1}{32}$ in. (0·8 mm) maximum, contained within an area of not less than $\frac{1}{2}$ in. (12½ mm). The spacing of individual pores to be not less than $\frac{1}{32}$ in.
6. Oxide inclusions up to $\frac{1}{16}$ in. diameter acceptable.
7. There should be no more than eight individual defects enumerated above in any one length of 6 in. of weld (*e.g.* six pores and two oxide films).

The application of these three individual standards resulted in vessels that were pressure tight, mechanically sound, and which subsequently gave satisfactory service without corrosion or mechanical failure of the welded joints. Needless to say the excessively stringent requirements of Standard 3 resulted in an increased cost for the job concerned, and it is to be hoped that realistic standards of acceptance will be adopted in the future to the benefit of fabricators and users alike.

Great reliance is placed on radiography as a non-destructive quality control method and much time and money is expended in taking action following adverse radiographic reports. What is not so commonly realised, however, is that certain forms of planar defect characteristic of aluminium welded by the Mig process are far from easily detected by radiography. These defects, such as lack of inter-run fusion or lack of root penetration, can have a serious and profound effect upon the mechanical strength of the joint and can quite easily go undetected. Figure 8 shows such a defect which was missed by radiography and the tensile figures obtained indicate a joint efficiency of only 78%. It is interesting to note that, although such a low tensile figure was achieved, the specimen did not fail in the accepted sense in a bend test. As can be seen from the illustration, the lack of fusion is evident only on the side of the specimen. The standards for accepting bend tests state that no crack or discontinuity greater than a certain specific length shall appear on the outer convex surface and clearly, according to that particular form of words, this specimen passes. What is more serious, however, is that if this defect had been discontinuous it is possible that there would have been no evidence even on the sides of the bend test piece and yet the effect upon static tensile strength would still have been most serious. It is clear that there is a case for fundamental re-thinking concerning the application of bend testing to aluminium and its alloys in particular and ductile non-ferrous metal and alloys in general.

Perhaps the most important task in the immediate future is to assess the effect of typical defects under static and dynamic conditions, to determine the tests most suitable for the detection of the defects to which aluminium welds are prone, and the conditions under which such tests should be made to ensure that structures have a satisfactory performance. Systematic programmes in these fields are in progress at some research establishments and the results will be viewed with keen interest.

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UTRECHT MEETING, 1961

Factors Influencing the Properties of Welds in Aluminium

By J. C. Bailey, B.SC., F.I.M., *and G. W. Eldridge*, A.I.M.

The paper reviews the currently established procedures for Tig and Mig welding of aluminium and its alloys and the methods developed for testing the welds. Factors underlying the occurrence of defects are then discussed, paying attention to the principal defects that can arise: weld cracking, porosity, and oxide inclusions. Other inherent factors influencing properties are then considered: filler rod composition, the extent of the heat-affected zone, and welding variables such as speed of welding and current. Finally the properties attainable in practice are considered.

THE industrial application of aluminium welding during the past decade has led to the accumulation of much practical experience, in that the significant factors appropriate to good welding technique and quality control are now well understood. In the U.K. this has enabled the British Standards Institution to lay down recommendations for standard welding procedures that are acceptable to users and inspection authorities. Attention is now being centred upon acceptable methods of testing welds and welders —leading, it is hoped, to the establishment of precise standards of weld quality for various purposes.

Weldable Aluminium Materials

Materials commonly used in Great Britain for general engineering purposes are specified in British Standards 1470/1477 and 1490. The following groups are normally welded:

Wrought

(i) Pure aluminium
(ii) Aluminium-manganese alloys
(iii) Aluminium-magnesium alloys
(iv) Aluminium-magnesium-silicon alloys

Cast

(v) Aluminium-magnesium alloys, aluminium-silicon alloys, and aluminium-silicon-copper alloys in the form of castings are occasionally incorporated into welded components.

The materials concerned are listed in Table I.

The welding process usually reduces the strength of the welds and adjacent zones to that of the material in its annealed condition: in the case of the heat-treatable (Al–Mg–Si) alloys this is considerably below the strength possible by full heat treatment, but sometimes the complete weld assembly can be given a final heat treatment to produce high weld efficiencies.

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Development of Standard Welding Procedure in the U.K.

The standard of welding demanded for metal structures, such as pressure vessels and atomic energy equipment, has forced up the general standard of weld quality; equipment has been made more reliable, standard welding techniques and edge preparations have been evolved, and test methods have been developed for inspection up to Class 1 Standards. These welding techniques are now being embodied in British Standards, such as BS.3019, Part 1, "*General Recommendations for Manual Inert-Gas Tungsten-Arc Welding*", which details suitable edge preparations, electrode size, filler metal, welding current, gas flow, etc., for given material thicknesses, together with suitable filler wire compositions. A similar document, dealing with the metal-inert-gas (Mig) welding process is in course of preparation.

Details of welding rods for the Tig process are contained in BS.2901, Part 1, "*Filler Rods and Wires for Inert-Gas Arc Welding, Gas Shielded Tungsten-Arc Welding*" and for the Mig process in BS.2901, Part 2, "*Filler Rods and Wires for Inert-Gas Arc Welding, Gas-Shielded Metal-Arc Welding*". The compositions of the materials contained in these Standards are given in Table II.

Testing procedures

Discussions are in progress on methods of testing welds, with the objective of producing a British Standard on recommended methods of testing. This will lay down standard methods to be adopted—tensile

Table I — Aluminium material compositions suitable for welding

Group	Specification BS.1470/77	Composition % Al	Cu	Mg	Si	Fe	Mn	Ni	Zn	Cr
(i)	1	99·99 min	(Cu+Si+Fe 0·01 max)							
,,	1A	99·8 min	0·02 max	—	0·15 max	0·15 max	—	—	—	—
,,	1B	99·5 min	0·05 max	—	0·3 max	0·4 max	0·05 max	—	—	—
,,	1C	99 min	0·10 max	—	0·5 max	0·7 max	0·1 max	—	0·10 max	—
(ii)	N3	rem.	0·15 max	—	0·6 max	0·7 max	1·0–1·5	—	0·1 max	—
(iii)	N4	rem.	0·10 max	1·8–2·7	0·6 max	0·7 max	0·5 max	—	0·1 max	0·5 max
,,	N5	rem.	0·10 max	3·0–4·0	0·6 max	0·7 max	1·0 max	—	0·1 max	0·5 max
,,	N5/6	rem.	0·10 max	3·5–5·5	0·6 max	0·7 max	1·0 max	—	0·1 max	0·5 max
,,	N6	rem.	0·10 max	4·5–5·5	0·6 max	0·7 max	1·0 max	—	0·1 max	0·5 max
(iv)	H9	rem.	0·10 max	0·4–0·9	0·3–0·7	0·6 max	0·3 max	—	0·1 max	—
,,	H19	rem.	0·10 max	0·4–1·5	0·60–1·3	0·6 max	0·2 max	—	0·1 max	0·10 max
,,	H20	rem.	0·15–0·40	0·8–1·2	0·4–0·8	0·7 max	0·2–0·8	—	0·2 max	0·15–0·35
,,	H30	rem.	0·10 max	0·4–1·5	0·60–1·3	0·6 max	0·40–1·0	—	0·1 max	0·3 max
	BS.1490									
(v)	LM5	rem.	0·1 max	3·0–6·0	0·3 max	0·6 max	0·3–0·7	0·1 max	0·1 max	—
,,	LM6	rem.	0·1 max	0·10 max	10·0–13·0	0·6 max	0·5 max	0·1 max	0·1 max	—
,,	LM8	rem.	0·1 max	0·3–0·8	3·5–6·0	0·6 max	0·5 max	0·1 max	0·1 max	—

testing, macro-examination, fracture and bend tests, crack detection and radiographic examination methods; the frequency of testing and minimum requirements could be ultimately laid down in particular application standards. A series of radiographs depicting typical weld defects, such as porosity, tungsten inclusions, and lack of penetration has been issued by The British Welding Research Association.[1] A code of practice for aluminium pressure vessels is also being prepared by the British Standards Institution and will eventually incorporate data on permissible stresses in welded components and on test requirements.

Visual examination, tensile tests, and radiography can give useful information when applied intelligently and enable weld quality to be accurately and reliably assessed. A sufficient number of tests must be made, of course, and on important work it may be necessary to subject every length of weld to radiographic examination. The nick-break test permits the examination of the fracture at a predetermined position in the weld. It is a useful test for determining general weld quality though it has been criticised on the grounds that the site of the fracture is not necessarily the least sound region in the weld. For Mig welds it is considered that complete freedom from porosity is an unrealistic criterion; porosity is inherent in welds made by this process and the practical goal should be a series of radiographic standards showing the amount and distribution of porosity to be permitted for various classes of work. It will, of course, be necessary to know the quantitative effect of porosity on weld strength, and test data are being accumulated with this object in mind.

Certain tests are considered to be unsuitable for general use in the practical assessment of weld quality: these include the Charpy or Izod impact tests, tensile tests of all-weld-metal specimens, microscopic examination, and shear tests on fillet welds.

Such tests are valuable in research and in development work on processes or materials, but as routine

Table II — Composition of filler/electrode wires

Specification BS.2901	Composition, % Al	Cu	Mg	Si	Fe	Mn	Ni	Zn	Cr	Others
G1	99·99 min	—	Cu+Si+Fe 0·01 max*		—	—	—	—	—	—
G1A	99·8 min	0·02 max	—	0·15 max*	0·15 max*	—	—	—	—	—
G1B	99·5 min	0·05 max	—	0·3 max*	0·4 max*	0·05 max	—	—	—	—
G1C	99 min	0·10 max	—	0·5 max*	0·7 max*	0·1 max	—	0·10 max	—	—
NG2	rem.	0·10 max	0·25 max	10·0/13·0	0·6 max	0·5 max	0·2 max	0·2 max	—	Sn 0·05 max Pb 0·05 max
NG21	rem.	0·10 max	0·25 max	4·5/6·0	0·6 max	0·5 max	0·2 max	0·2 max	—	Sn 0·05 max Pb 0·05 max
NG3	rem.	0·15 max	—	0·6 max	0·7 max	1·0/1·5	—	0·1 max	—	Ti 0·20 max
NG4**	rem.	0·10 max	1·8/2·7	0·6 max	0·7 max	0·5 max	—	0·1 max	0·5 max	Ti 0·20 max
NG5	rem.	0·10 max	3·0/4·0	0·6 max	0·7 max	1·0 max	—	0·1 max	0·5 max	Ti 0·20 max
NG6	rem.	0·10 max	4·5/5·5	0·6 max	0·7 max	1·0 max	—	0·1 max	0·5 max	Ti 0·20 max
NG7**	rem.	0·10 max	6·5/7·5	0·6 max	0·7 max	0·5 max	—	—	0·5 max	Ti 0·20 max

* It is desirable that %Si is less than %Fe
** BS.2901, Part 1 only.

Table I — Aluminium material compositions suitable for welding

Group	Others	U.S.A. (A.A.)	Some Similar Overseas Specifications France		Germany (DIN 1712 & 1725)	Italy	I.S.O.
(i)					Al 99·99		
,,			A8		Al 99·8		Al 99·8
,,			A5		Al 99·5	UNI 3566	Al 99·5
,,		1100	A4		Al 99	UNI 3567	Al 99·0
(ii)	Ti 0·20 max	3003	A–M		AlMn	UNI 3568	Al–Mn1
(iii)	Ti 0·20 max	5052	A–G2			UNI 3574	Al–Mg2
,,	Ti 0·20 max	5154	A–G3			UNI 3575	Al–Mg3
,,	Ti 0·20 max						
,,	Ti 0·20 max	5356	A–G5		AlMg5	UNI 3576	Al–Mg5
(iv)	Ti 0·30 max	6063	A–GS	E	AlMgSi	UNI 3569	Al–MgSi
,,	Ti 0·30 max						
,,	Ti 0·30 max	6061					
,,	Ti 0·30 max		A–SG		AlMgSi		Al–SiMg
(v)	Sn 0·05 max; Pb 0·05 max; Ti+Nb 0·2 max					UNI 3058	
,,	Sn 0·05 max; Pb 0·1 max	13	A–S13	G	AlSi	UNI 3047	Al–Si12
,,	Sn 0·05 max; Pb 0·1 max; Ti+Nb 0·2 max						Al–Si5Mg

tests they give very little positive information because it is so difficult to interpret the results in practical terms. Indeed they may even be misleading and so cause the rejection of work that is satisfactory for its purpose. This criticism can also be made of ultrasonic testing in the present state of knowledge, but it is hoped that this will develop into a useful and reliable non-destructive test method for aluminium weldments.

Control of welding defects

Cracking

A survey of the literature on weld cracking in aluminium alloys shows that many contradictions exist. For example, on the one hand it has been shown that the risk of cracking increases with iron and silicon contents (at impurity level); on the other, that high-purity aluminium is more prone to cracking than commercial-purity aluminium. Again, a reasonable content of low-melting-point eutectic is advantageous, yet Al–Mn alloy—which contains no low-melting eutectic—has less tendency to weld cracking than Al–Mg–Si alloys, which do.

It may be that such apparent differences arise from the use of different methods of crack testing—each causing its own degree of non-equilibrium in the system, or each being preferentially sensitive to one type of cracking.

The problem of cracking during the welding of aluminium has been the subject of study by several establishments, notably the work of Pumphrey and others at the University of Birmingham which propounded a shrinkage-brittleness theory of cracking[2] that has been recently considered in relation to a generalised theory of cracking above the solidus.[3] The earlier work by the A.D.A. Team established reliable means of recording the tensile properties of cast aluminium alloys at elevated temperatures—up to those, near the melting point, at which coherence of the primary crystal network was lost. With a given system the tendency to cracking is related to the difference between the cohesion temperature and the solidus temperature; the sensitivity of a given composition is, however, affected by variations in the rate of cooling and by other factors modifying the degree of equilibrium obtained.

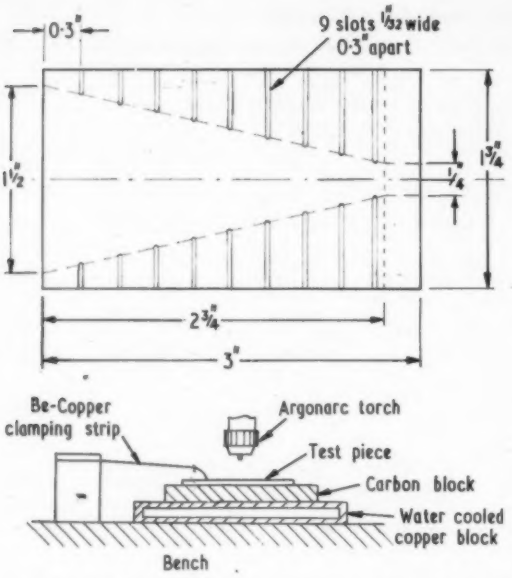
The work on super-solidus cracking has shown that in simple alloy systems the degree of cracking will be at a maximum with the following concentrations of the second component:

Copper	3%
Magnesium	4%
Silicon	0·6%
Mg_2Si	1%

The severity of cracking is not the same with each component and it will be appreciated that the concentration of alloying element to produce maximum cracking may be modified by the presence of other elements or by specific cooling conditions.

Weld cracking has been observed at temperatures below the solidus in some alloy series; notably Al–Cu–Mg, Al–Cu–Mg–Si, and Al–Zn–Mg alloys. The A.D.A. Team concluded that its occurrence depended on the ductility of the metal, on the conditions of stress to which the material was subjected during cooling to ambient temperature, and on the amount of cracking that occurred at temperatures above the solidus. It was noted that the ring casting test used in

1—*Ring casting mould used in research on aluminium weld cracking*



2—Houldcroft 'fishbone' crack test specimen used for ¼ in. thick material

this work did not produce sub-solidus cracking in all alloys where weld cracking occurred in the solid state, and since the total contraction from the solidus to room temperature produces a strain of only about 1% (which would not be expected to lead to fracture) the notch effect at the weld ends must be responsible for the imposition of localised high strains leading to cracking. It is significant that the ductility of the unfused sheet material affects the propensity of a weld to crack; it was noted that sub-solidus cracking occurred in certain Al–Zn–Mg alloys welded in the heat-treated condition but not in the same alloys when welded in the annealed condition, the sheet then possessing higher ductility.

The A.D.A. Team used chiefly a ring casting test with cast iron mould and solid cast iron core (Fig. 1); also a restrained-weld test jig. This clearly differentiated between the cracking susceptibilities of various alloys considered at that time, but it would not necessarily be sufficiently selective when considering slight composition variations. Subsequent work by the British Welding Research Association on the effect of various filler alloys in the welding of Al–Mg–Si alloys showed that a restrained-weld test was not sufficiently severe, and a simple cracking test was devised[4] which has since been used for work on the welding of heat-treatable alloys (Fig. 2). Investigations in many parts of the world have shown it necessary to devise methods of evaluating weld cracking susceptibilities, and a very extensive review of these has been made recently.[5] It must be acknowledged that any one type of cracking test is unlikely to cover the whole range of cracking susceptibilities that may be met in the future development of weldable aluminium alloys. It must also be recognised that such tests are of immediate use in development work on alloys and filler wires, and that cracking in weldments on the production floor may be influenced by other factors particular to the specific job concerned. Where particular difficulty arises in production, the welding metallurgist may be able to avoid cracking by using an alternative filler wire, but more probably he will need to find out whether the welding sequence is appropriate, whether the welding conditions are satisfactory, or perhaps whether preheating is advisable.

Porosity

The solubility of hydrogen in molten aluminium is about 0·7 cu.cm per 100 g, whereas in the solid metal just below the solidus it is only 0·036 cu.cm per 100 g: consequently any hydrogen in excess of this absorbed during melting will be rejected from solution during freezing, to form porosity. That hydrogen is the main source of porosity in aluminium welds is not disputed, although pores may in some instances be due to entrained argon or air. When welding under an inert gas screen, direct reduction of the water vapour in the atmosphere would not be counted a major source of hydrogen but vapour from this source may be present in the oxide film on the surface of the parent metal or filler/electrode wire. From time to time the initial hydrogen content of the plate or filler materials has been blamed for excessive porosity but this is not today considered a serious contributor to the problem. It is, however, accepted that the porosity level may vary according to composition, *e.g.*, Al–5%Mg filler gives a lower apparent porosity count than does Al–5%Si filler under similar conditions. That assessment of the origins of porosity is no simple matter is probably due to minor variations in the testing method introduced by investigators; for example, it has been shown that in Mig welding the welding voltage affects the porosity level.[6] This work indicated that low-voltage arcs (18V) where short circuiting was frequent, resulted in welds having 1% voids, whilst welds made at 26 V gave less than 0·1% voids. These tests were made on Al–Mg plate NP5/6 (BS.1477) using Al–5%Mg electrode wire.

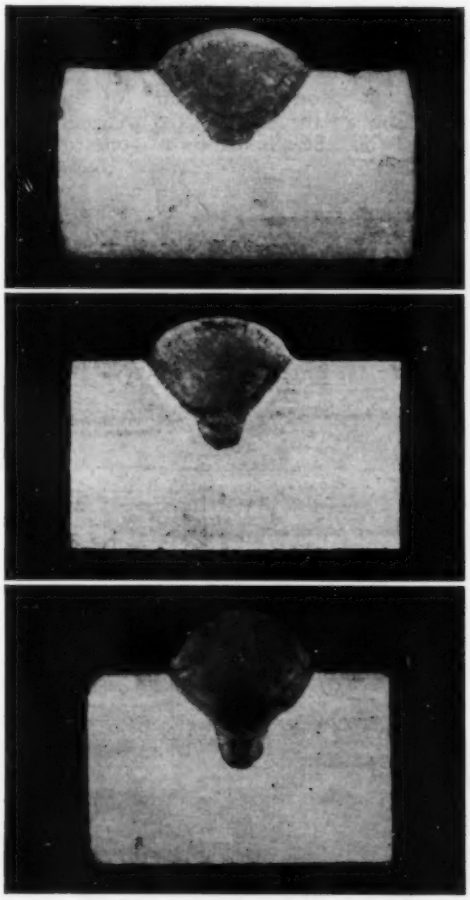
Welding current also affects the degree of porosity in Mig welding; low currents lead to high rates of cooling and solidification, causing higher porosity counts. This effect of low current is even more pronounced with electrode wire of inferior surface condition.

Porosity is at a generally higher level in Mig welding than in Tig welding and it is accepted that this difference is mainly due to the higher ratio of surface area to cross section volume of the electrode wires and the difficulty of keeping long lengths of the wire free from contamination while in stock. This leads to reluctance to use this process in some industries although there is no evidence that the mechanical strengths of Mig welds are inferior to those of Tig welds. Nevertheless porosity is a defect which can be readily observed on radiographic examination and it leads to rejections in many cases where such action is probably not justified. The British Welding Research Association has published a series of radiographs exhibiting defects and has also devised a system of recording porosity.[7] An investigation is at present in progress with the object of assessing quantitatively the effects of porosity and this will include both static and dynamic tests. This work should lead to the establishment of

reasonable standards of radiographic inspection for aluminium welds.

Oxide inclusions

With proper control of the welding conditions the porosity level can be contained within acceptable limits but other defects can arise in aluminium welds which will have a greater significance in their effect on weld properties. The refractory oxide skin that develops on the metal surface during heating can be very tenacious and the presence of such a skin on the underbead may prevent fusion between the two plate edges at the root of the joint. A similar film may build up at the junction between the weld metal and the parent metal at the side of a weld, and fragments of oxide may be contained within the fused zone. With tungsten-inert-gas welding, prolonged use at high currents may cause collapse of the electrode tip and lead to inclusions of tungsten in the weld; similarly, in the metal-inert-gas process copper inclusions can be derived from the contact tube.



(*a*) 250 in./min, 275 amp; normal arc with signs of penetration finger
(*b*) 275 in./min, 300 amp; critical finger with occasional voids
(*c*) 300 in./min, 330 amp; defective weld with tunnels

3—*Macrosections of Mig bead runs in 99% purity aluminium plate, showing effect of current on tunnel formation*

Of these defects the most serious effect upon mechanical properties is produced by oxide films preventing complete fusion, but tungsten or copper inclusions may affect corrosion resistance of the joint.

Tunnelling

The high thermal conductivity of aluminium is one property that contributes to the difficulty of welding thick sections, and to avoid preheating it is obviously desirable to weld under high currents. With the Tig process there appears to be an upper limit of about 350 amp above which tungsten loss becomes obvious even with large diameter electrodes, although higher currents than this have been used with success. With the Mig process there is also an upper limit above which defective welds are produced. At very high currents the appearance of the bead indicates that the deposit is unsatisfactory; it is characterised by blackening and irregular lumpy deposits, the condition being known as 'puckering'. Between this current level and the normal deposit current, however, a range occurs in which the weld quality is unsatisfactory, but the bead appearance is not markedly different from that of a normal weld. In this region elongated voids occur in the base of the weld, arising from excessive turbulence in the weld pool; such defects are known as 'tunnels', and they are very obvious in a cross-section of the weld[8] (Fig. 3). It is impossible to control this feature by observation during welding but it has been shown that the current at which tunnelling occurs is affected by variations in welding procedure, such as the gun angle, and also by the effectiveness of the argon screen.[9,10] Recent work reported satisfactory welds in 1 in. (25 mm) plate in Al–Mg alloy NP5/6 in two passes with currents up to 600 amp and arc voltages between 28 and 32 V. These welds were made with conventional equipment without special argon screens, but particular attention was paid to torch angle and the argon flow. The arc travel speeds were approximately 12 in./min (30 cm/min) and the welds were completely free from oxide enfoldment.[11]

The defects considered in the foregoing are those which experience has shown to be the most serious in aluminium welding as such, but general welding faults, such as misalignment, poor bead shape, and incorrect filler, must also be avoided. The defects considered can be observed by radiographic examination, except that it is possible for fine oxide films, preventing complete side or inter-run fusion, to remain undetected. This is illustrated in Figs. 7–10.

Properties of Aluminium Welds

Occurrence of heat-affected zone

Except perhaps when the materials are used in the annealed or cast conditions, the properties of aluminium and its alloys are modified on either side of the weld bead by the intense welding heat. The extent of these effects depends on the total heat input and to a lesser extent on the time interval; in turn the heat input depends on the welding process used, the number of passes, and the speed of welding.

The inert-gas arc-welding processes, with their intense heat sources, produce a heat-affected zone somewhat narrower than would result from oxy-acetylene welding. The zone is, however, still of considerable significance in single-pass butt welds; it

usually extends across twice the material thickness on each side of the weld, and in multipass welds it may spread substantially farther. Except for materials welded in the annealed condition, the heat-affected zone is characterised by a drop in hardness but a hardness survey may not necessarily indicate the relative mechanical properties in the weld area. Work by the A.D.A. Team showed the interesting pattern of thermal changes that occur in aluminium welded by the various methods then available. For example, in butt welds between two sheets 0·080 in. (2 mm) thick, material 1 cm from the welded edge was heated above 300°C. for some 15 sec during Tig welding, whilst material 2·5 cm from the welded edge was similarly heated for 40 sec during oxy-acetylene gas welding. The differences in temperature decay times in the close vicinity of the weld were substantial, and it was noted that the temperature distribution in the heat-affected zone was much less affected by variations in oxy-acetylene welding conditions than by variations in arc welding conditions.

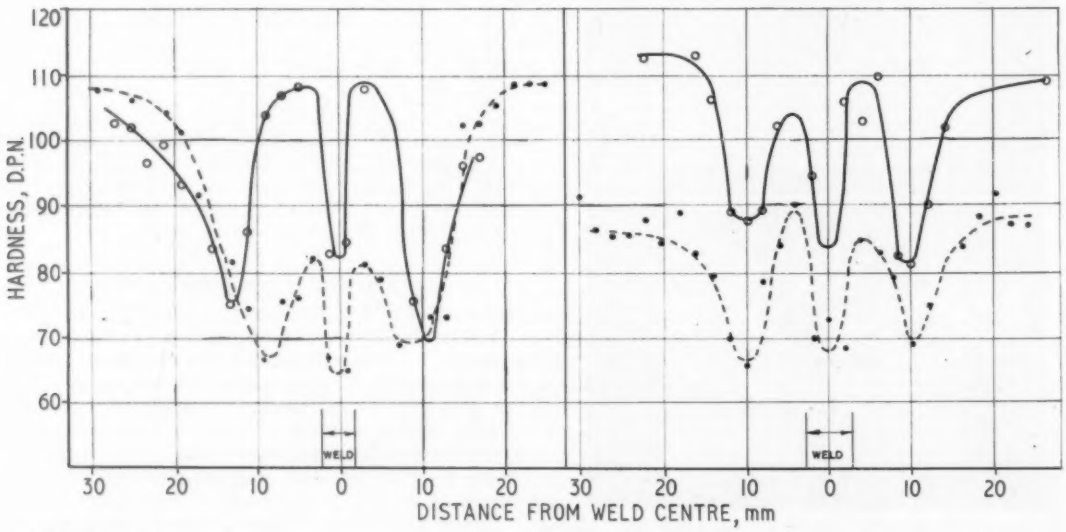
Dividing aluminium alloys broadly between those which are strengthened by heat treatment and those which are not, it can be stated that materials in the latter group which have been subjected to work hardening suffer a loss in hardness when heated in the region of 250°C.; the degree of loss depends on the temperature and duration, but a simple generalisation cannot similarly be stated for the former group. Assuming that the heat-treatable material has been fully heat-treated, application of further heat will cause excess precipitation or over-ageing, leading to some loss in mechanical properties. At higher temperatures the material will become fully softened. Further heating up to the solidus, followed by slow cooling, would not have any significant effect on the hardness, but precipitation from the supersaturated solid solution will have occurred progressively; this, together with possible grain growth, will have further modified the physical properties. Up to this stage the original properties of the heat-treated sheet can be almost entirely recovered by re-heat-treatment. Heating above the temperature of incipient fusion has a deleterious effect upon the mechanical properties, particularly the ductility, which will not be restored by re-heat-treatment. The rapid transfer of heat from the weld area to the surrounding metal, resulting from the high thermal conductivity of aluminium, has a quenching effect on the material adjacent to the weld pool, which will therefore subsequently age harden at room temperature or respond to precipitation treatment, depending on the alloy. The speed of quenching required to produce the solution-treated condition varies between alloys, and the Al–Zn–Mg alloys are notable for their tolerance to quench speed. A hardness survey of the heat-affected zone of a weld in material heat-treated before welding often shows a reduction in hardness at the outer extremities; the inner zone has been re-solution-treated by the welding heat and the outer zone has severely over-aged (Fig. 4).

Uncontrolled bend tests on welds can give non-uniform bends due to these variations, so the test shown in Fig. 5 is used; but it will not detect internal defects (Fig. 6).

Despite the good understanding of the various characteristics of the heat-affected zone, or perhaps because of this, the elimination of zones of inferior strength is still an intractable problem from the metallurgical aspect. The undesirable effects can be reduced in two ways:

(*a*) By using a filler rod that overmatches the strength of the parent metal and leaves a deposit whose final strength is greater than would otherwise be the case.

(*b*) By welding so rapidly that the softening effect of the welding heat is kept to a minimum. The higher heat input of Mig



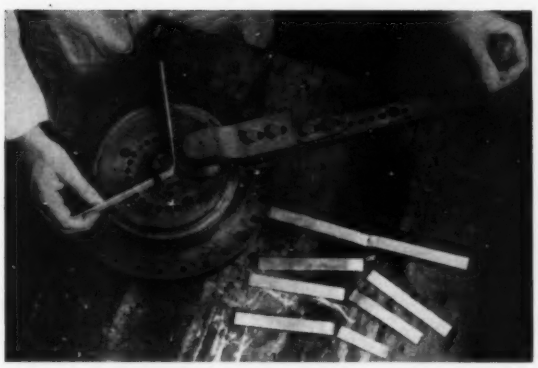
(*a*) Fully heat treated

	Tensile strength	*Elong. on 2 in.*
— As welded	13·8 tons/sq.in.	8%
– Precipitation treated 3 hr at 185°C	15·9 tons/sq.in.	5%

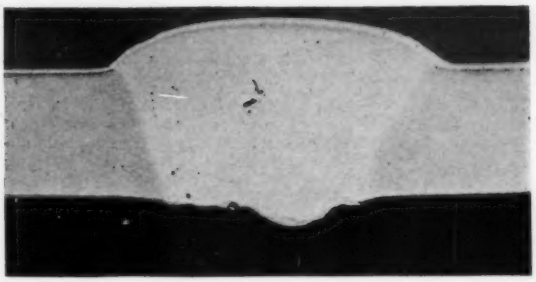
(*b*) Solution treated

	Tensile strength	*Elong. on 2 in.*
— As welded	13·5 tons/sq.in.	12%
– Precipitation treated 3 hr at 185°C	16·3 tons/sq.in.	5½%

4—*Examples of hardness surveys across Mig welds in ¼ in. thick Al–Mg–Si alloy HP.30W and HP.30WP welded with Al–12% Si wire*

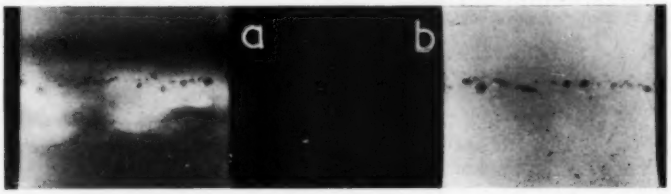


5—*Controlled bend test apparatus*



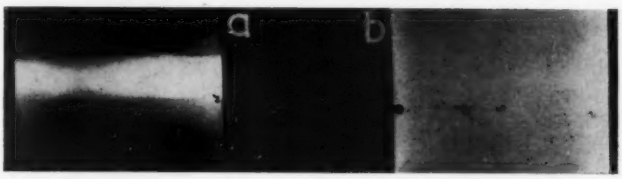
6—*Cross section of Mig weld in Al–Mg–Si alloy welded with Al–12% Si wire, showing central defect of type not affecting controlled bend test result. Etched 10% sodium hydroxide* ×4

7—*Radiographs of Mig welds in ½ in. thick Al–5% Mg alloy, showing gross porosity:* (a) *with reinforcement retained;* (b) *with reinforcement removed*



8—*Tensile fractures of samples shown in Fig. 7:* (a) *Fracture outside weld, joint efficiency 100%;* (b) *fracture at weld showing porosity, joint efficiency 80%*

9—*Radiographs of Mig welds in ½ in. thick Al–5% Mg alloy;* (a) *with reinforcement retained;* (b) *with reinforcement removed. Porosity in* (b) *is much less severe than in sample shown in Fig. 7*



10—*Tensile fractures of samples shown in Fig. 9:* (a) *Fracture outside weld, joint effic.ency 100%;* (b) *fracture at weld showing lack of root fusion not revealed on radiograph, joint efficiency 80%*

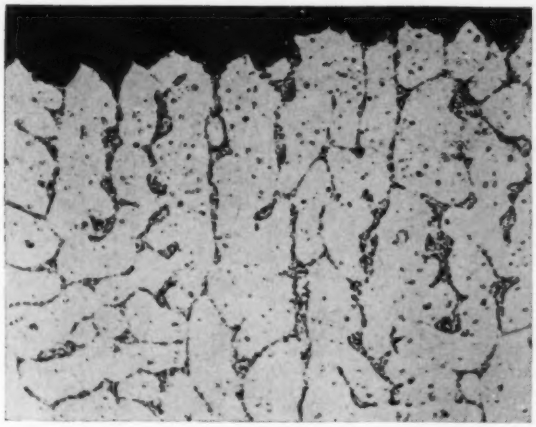
Table III

Filler/electrode wires for welding aluminium

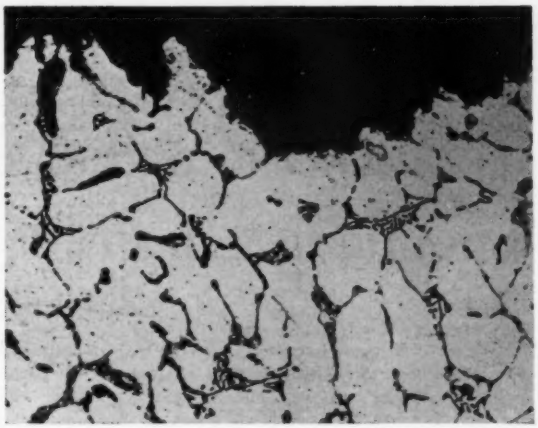
Filler/electrode wire designation

Parent Metal Designation	1	1A	1B	1C	N3	N4	N5	N5/6	N6	H9	H19	H20	H30	LM5	LM6	LM8
1	G1 (G1C)[1]															
1A	G1A (G1C)[1]	G1A (G1C)[1]														
1B	G1B (G1C)[1]	G1B (G1C)[1]	G1B (G1C)[1]													
1C	G1C	G1C	G1C	G1C												
N3	G1C	G1C	G1C	G1C	NG3											
N4	NG6	NG6	NG6	NG6	NG6	NG6										
N5	NG6	NG6	NG6	NG6	NG6	NG6	NG6									
N5/6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6								
N6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6							
H9	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG21 (NG6)[2]						
H19	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG21 (NG6)[2]	NG21 (NG6)[2]					
H20	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]				
H30	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG6 (NG2, NG21)[1]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]	NG21 (NG6)[2]			
LM5	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6	NG6		
LM6	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	
LM8	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21	NG2, NG21

Notes: [1] Where cracking is persistent. [2] For colour matching on anodising.



11—*Structure in Tig weld between ¼ in. thick Al–3½% Mg sheet and ¼ in. thick Al–12% Si casting using Al–12% Si filler Etched hot 25% HNO_3* ×400



12—*Structure in Tig weld between ¼ in. thick Al–3½% Mg sheet and ¼ in. thick Al–12% Si casting using Al–5% Mg filler Etched hot 25% HNO_3* ×400

welding and the consequent higher speeds possible, result in smaller heat-affected zones than with Tig welding.

Filler metal

The development of welding techniques for aluminium has been following a logical sequence: First the establishment of data for welding the then existing alloys with parent metal and other fillers; next the understanding of the advantages of dissimilar fillers afforded by work such as that by the A.D.A. team; then the development of special complex filler compositions for heat-treatable alloys such as Al–Cu–Mg–Si alloys, and most recently the development of weldable medium strength Al–Zn–Mg alloys with higher weld efficiencies than those obtainable with the Al–Mg–Si series.

The various grades of pure aluminium and Al–1¼% Mn alloy are generally considered to be of good weldability with filler rods of base metal composition. With all these compositions it has been shown to be important that the iron content should exceed the silicon content (preferably by 50%): perhaps this is why high-purity aluminium presents difficulty—because its Fe/Si ratio does not always meet this requirement. The Al–Mg alloys used in the U.K., *i.e.*, 2¼, 3½ and 5% magnesium can all be welded with filler wire of the same composition. The original A.D.A. Team investigation showed that the critical magnesium content for maximum cracking was 4%, but the commercial alloys contain manganese, iron, and silicon, and the commercial concentration of these elements produces a critical magnesium content of 1·5–2%. Industrial experience has confirmed that cracking problems are greater with the 2¼% Mg alloy than with alloys of higher magnesium content.

When adopting a filler wire of composition at variance with the base metal composition the degree of dilution provided by the joint configuration must be taken into account; this will vary from 25 to 40% in fillet welds to approx. 90% in close butt welds. In the 2¼% Mg alloy, with the lower dilution factor, a filler rod of 3·5% Mg alloy will produce a weld composition above the critical concentration, but to allow for the higher dilution of heavy close butts, a 5% Mg alloy rod is advisable. Therefore, to reduce the number of variables, the latter composition is generally accepted for welding the general range of Al–Mg alloys containing between 2% and 5·5% Mg. A guide to filler metal selection is given in Table III.

Mechanical properties

All the foregoing factors influencing weld properties have been considered both separately and together during the development of welding techniques for aluminium, and during the past few years the quality of welds and their strength have in consequence been gradually improved. But there is still ample scope for further improvement, as shown by Table IV, which gives values drawn up from consideration of a very large number of test results provided by various British sources. It will be noted that this table indicates values for tensile strength only; information on proof stress and elongation values has not been included since the level of these properties is markedly affected by the size of the weld in relation to the size of test piece.

The table is confined to wrought alloys since information on welding of castings is far less extensive. However, applications do arise where the use of fusion welding to make joints between cast and wrought products, or between two cast components, is an obvious production requirement. Experimental work is at present in progress to obtain further information on weldability of the materials and the properties of joints between dissimilar materials. In earlier work[12] the properties of butt welds between LM4-M, LM5-M or LM6-M and NS3-½H, NS6-½H or HS30-WP were considered and the further series will deal with butt welds made by both Mig and Tig processes between LM5, LM6 or LM8, and PIB-M or NP5/6-M. In the case of the Al–12% Si alloy (LM6) both sand cast and die cast forms are to be investigated, and in the Al–Si–Mg alloy (LM8) both precipitation-treated and fully-heat-treated conditions will be used. The series will include three filler/electrode wire materials—

Table IV — Mechanical properties of butt-welded joints using inert-gas arc-welding processes

Parent Metal (BS.1470–77)	*Filler or Electrode Alloy (BS.2901)*	*Tensile Strength* Minimum, tons/sq.in. (kg/sq.mm)*	*Typical, tons/sq.in. (kg/sq.mm)*	*Thickness Range, in. (mm)*	*Appropriate Welding Process*
S1	G1	3 (4·7)	3½ (5·1)	$\frac{1}{16}$ (1·6)	Tig
S1B–O, P1B–M	G1B	4 (6·2)	4¾ (7·5)	⅛ (3·2) to 1 (25·4)	Mig/Tig
S1C–O	G1C	4 (6·2)	4¾ (7·5)	up to ¼ (6·3)	Mig/Tig
S1C–½H, –H	G1C	4 (6·2)	5 (7·9)	up to ¼ (6·3)	Mig/Tig
NS3–O	NG3	5¾ (9·0)	6¼ (9·8)	up to ¼ (6·3)	Mig/Tig
NS3–½H, –H	NG3	5¾ (9·0)	7½ (11·8)	up to ¼ (6·3)	Mig/Tig
NS4–O, NP4–M	NG4/NG5/NG6	11 (17·3)	12 (18·9)	up to ½ (12·7)	Mig/Tig
NS4–¼H, –½H	NG4	11 (17·3)	12½ (19·7)	up to ¼ (6·3)	Mig
NS5–O	NG5	13½ (21·3)	14½ (22·8)	up to ¼ (6·3)	Mig/Tig
NS5–O	NG6	14 (22·0)	14½ (22·8)	up to ¼ (6·3)	Mig/Tig
NS5–¼H	NG5	13½ (21·3)	15 (23·6)	up to ¼ (6·3)	Mig/Tig
NS5–¼H	NG6	14 (22·0)	15 (23·6)	up to ¼ (6·3)	Mig/Tig
NP5/6–O, –M	NG6	16 (25·2)	17 (26·8)	⅛ (6·3) to 1 (25·4)	Mig/Tig
NS6–O	NG6	16 (25·2)	17½ (27·5)	up to ¼ (6·3)	Mig/Tig
HS/HP20–W, –WP	NG6/NG21	11 (17·3)	12 (18·9)	up to ⅜ (9·5)	Mig/Tig
HS/HP30–W, –WP	NG6/NG21	11 (17·3)	13 (20·5)	up to ⅜ (9·5)	Mig/Tig
HS/HP30–W, –WP	NG6/NG21	11 (17·3)	13 (20·5)	over ⅜ (9·5) up to 1 (25·4)	Mig

* All the properties quoted are for materials in the as-welded condition. Joints of H20 and H30 should have a minimum tensile strength of 17 tons/sq.in. (26·8 kg/sq.mm) after full re-heat-treatment. No values can be laid down for these joints after precipitation treatment alone, because in that condition the properties vary considerably with thickness and welding technique. The "Minimum Tensile Strength" values should be used for design purposes; the "Typical Tensile Strength" values are added for information only.

Al–5% Mg alloy, 12% Si alloy, and 5% Si alloy—to establish the relative merits of these when making joints between Al–Si–Mg alloy castings and Al–Mg alloy sheet materials. Previous tests on a number of welds between these two materials, using Al–5% Mg and 12% Si filler materials, showed that the properties obtained with the 12% Si filler were superior: no massive Mg_2Si was formed, possibly owing to the lower melting temperature of the filler metal and consequent smaller amount of fusion of the Al–Mg alloy. Typical structures are shown in Figs. 11–12.

Properties at sub-zero temperatures

In recent years a number of investigators have reported the results of their tests on some aluminium alloys at sub-zero temperatures.[13,14] This work was instigated as a result of the interest shown in the commercial transportation and storage of liquid methane, and the knowledge that ferritic steels were liable to suffer from brittle fracture at sub-zero temperatures. The boiling point of methane is −160°C., but the investigations were generally made in liquid nitrogen at −196°C. To study the effect of stress raisers on the crack propagation of the materials, a number of specialised tests were used, including centrally notched tensile tests, U.S. Navy tear tests,[15] and Tipper Tests.[16] These tests showed that cracks were no more readily formed or propagated at −196°C than they were at room temperature. Whilst samples containing welds yielded lower values than the unwelded samples, it was quite clear that the welding operation had not induced any tendency to self-propagate cracks. Fatigue tests were also carried out at −196°C. on T-sections constructed by double fillet welds, reverse bending stresses under zero mean stress being applied. The maximum alternating stress value for a given endurance at −196°C. was about 50–60% higher than the corresponding value at room temperature, and this applied over the full range of endurances covered.

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UTRECHT MEETING, 1961

Some Notes on the Design of Chemical Equipment in Aluminium

By E. F. Boon and F. C. A. A. van Berkel

The properties of aluminium as a material of construction for chemical equipment are compared with those of steel, using various parameters: the price parameter for strength $G\rho/\sigma$; the price parameter for stability $G\rho^2/E$; the thermal stress parameters $\sigma/\alpha E$, λ, $\lambda/\rho c$, $\lambda\rho c$ and the strength/density parameter σ/ρ.

The design rules for flat aluminium gaskets are elucidated. A design study of an aluminium tank for a liquefied methane tanker is shown.

The authors stress the need for research to determine the allowable stress in aluminium equipment for the chemical industry taking into account 1,000 load cycles, weld cracks and thermal stresses.

PURE aluminium and various aluminium alloys have properties, which make their use for the construction of chemical equipment often desirable.

In this paper these specific properties of aluminium will be discussed and compared with those of steel, showing as a result typical differences between construction in aluminium and in steel. A general review of the use of aluminium as a material of construction has been given by Banks and Smith.[1]

Compared with steel, the specific weight of pure aluminium and its alloys, the modulus of elasticity and—at least for the materials used for the construction of chemical equipment—the 0·2% proof stress and the ultimate tensile strength are generally lower; the allowable plastic deformation—at least for soft aluminium—the coefficient of thermal expansion, heat conductivity, electric conductivity, and specific heat are higher. The impact strength of aluminium does not decrease sharply at low temperatures, like that of steel. Various aluminium alloys have an outstanding corrosion resistance to many chemicals;[2] added to these properties are the low cross-section for absorption of thermal neutrons and the short half-life of the radioactive isotopes Al^{28} of 2·3 min, which make aluminium of interest to the nuclear engineer.

Aluminium is generally non-contaminating, and the aluminium salts are colourless and non-poisonous. It is non-magnetic and non-sparking, which latter property is an advantage in explosion dangerous areas.[3] At elevated temperatures the strength is generally poor and creep is excessive.

Consequently, chemical equipment is constructed in aluminium to provide: chemical resistance, no contamination, plastic deformation at low stresses, ductility at low temperature, light weight, non-sparking properties and low resistance to heat flow.

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Suitable Materials for Chemical Equipment

Today an enormous number of wrought, extruded, and cast aluminium types, varying from pure aluminium to non-heat-treatable and heat-treatable alloys, is available.[4,5] For the construction of chemical equipment, however, only those types are suitable which at least are easily weldable, and combine a good chemical resistance with a reasonable strength. The most important aluminium types that more or less satisfy these conditions are:

Non-heat-treatable

(*a*) *Pure aluminium:* purity ranging from 99·0 to 99·99%; high resistance to corrosion at high purities; low strength with high ductility; strength increases at the cost of the ductility with cold work; qualities varying from soft to hard; good weldability; high thermal and electrical conductivity at high purity.

(*b*) *Aluminium–Manganese alloy* (1·0–2·0% Mn): about the same properties as pure aluminium with slightly higher strength.

(*c*) *Aluminium–Magnesium—(Manganese) alloy* (0·5–6% Mg, 0–1·5% Mn): medium strength in the soft state; increased strength and decreased ductility with increased Mg content; stress corrosion might form a problem with Mg above 4–5%; good chemical resistance; strength increases at the cost of ductility with cold work; excellent weldability, though worse at higher Mg content.

The cold worked materials can be fully annealed by heating.

Table I

Typical physical properties at room temperature of pure aluminium, aluminium alloys, mild steel and stainless steel

	Pure aluminium (soft)	*Al-3% Mg (soft)*	*Al-5% Mg (soft)*	*Al–Mg–Si*	*Mild steel (soft)*	*Stainless steel (soft) 18/8/2½ Mo*
Classification	BS.1A	BS.N5	BS.N6	BS.H19	BS.1501–151 Grade A	ALSI 316
Specific weight, kg/cu.m	2700	2650	2600	2700	7850	7900
0·2% proof stress, kg/sq.mm	2·5	10	14	6·5		26
or lower yield stress, kg/sq.mm					21	
Ultimate stress, kg/sq.mm	7	22	27	12	37	55
Elongation on 5cm, %	30	17	17	18	28	35
Modulus of elasticity, kg/sq.mm	6700	7000	7000	7000	21000	200000
Impact strength, kg.m/sq.cm	10	3·5	4	6	10	20
Hardness, D.P.N.	18	45	60	30	130	150
Specific heat, kJ/kg°C.	0·9				0·46	0·495
Heat conductivity, kW/m °C.	0·20	0·145	0·116	0·175	0·05	0·014
Coefficient of thermal expansion, °C.$^{-1}$	24×10^{-6}	24×10^{-6}	24×10^{-6}	23×10^{-6}	$11{\cdot}7\times10^{-6}$	16×10^{-6}

Notes 1 kg/sq.mm = 0·64 tons/sq.in.
1 kJ/kg°C. = 0·239 Btu/lb °F.
1 kW/m °C. = 578 Btu/ft² hr °F./ft

Heat-treatable

Aluminium–Magnesium–Silicon alloy (0·3–1·5% Mg, 0·3–1·5% Si, 0–1·0% Mn): about the same strength as mild steel; good resistance to corrosion; good weldability, both of soft and hard material.

In Table I the various physical properties of these alloys are compared with those of mild steel 37 (BS.1501–151 grade *A*) and with soft stainless steel, 18% Cr–8% Ni–2·5% Mo (AISI 316).

The strength of the heat-treatable alloys, like Al–Mg–Si alloy, can be substantially increased by solution-heating the material, cooling it down rapidly and by finally ageing it at moderate temperatures. The strength will be decreased again if the material is heated to a higher temperature and cooled slowly; eventually the fully soft quality can be regained.

Properties of Welded Joints

In this paper the properties of the welded joints in chemical equipment should be mentioned.[5,8]

The deposited weld bead is a casting, which means that the strength and the elongation will have values more or less equal to those of cast aluminium of corresponding composition.

The zones alongside the welds will be more or less completely annealed, in the case of non-heat-treatable material, and will have properties similar to those of the soft quality. The strength could be regained by plastic deformation, but this is generally not possible. In case the aluminium alloy is heat-treated, the zone alongside the welds will also lose strength, which can be regained only by a re-heat-treatment, which is sometimes possible.

The welded joints normally appear to have approximately the same resistance to corrosion as the parent materials.

Allowable Stresses

Unwelded material

Equipment in structural steel is generally pressure tested in such a way that general plastic deformation does not occur. The working load is the test load divided by a safety factor, which is, in the temperature range between 0° and 300°C., often chosen as 1·5. The allowable design stress then becomes the yield stress at the working temperature divided by this safety factor. Many years of experience have shown that the choice of this safety factor gives a reasonable lifetime and that, for instance in a pressure vessel, 1000 load cycles can safely be supported.

The combined effects of the factors governing the allowable stresses, such as life, plastic deformation at load cycles, temperature cycles, and so on, are little known for steel and still less for the various aluminium alloys. Therefore a direct basis, to determine a realistic ratio between the working stress and the 0·1% or 0·2% proof stress, is not available.

However, in comparing aluminium with steel, the following considerations may be discussed:

(*a*) *Quality of aluminium*

The quality of aluminium is varying, because of the wide ranges in the various specification; this decreases relatively the allowable stress, as the low values will have to be used.

(*b*) *Modulus of elasticity*

The low modulus of elasticity—Young's modulus—decreases the stress peaks, caused by abrupt changes in cross-section; the Young's modulus of aluminium is approx. 7×10^3 kg/mm², so approx. ⅓ of the Young's modulus of mild steel.

(*c*) *Thermal stresses*

Failure due to thermal stresses can be caused by poor geometry of the structure, rapid temperature changes and by the material of construction. The ability of a material to withstand thermal stresses will be described using 4 typical, well defined thermal loads.

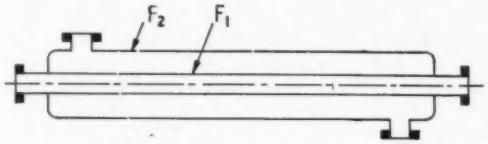
(i) *Stationary (time independent) temperature difference between two parts of a structure*

It can be calculated that the temperature difference ΔT causing a stress σ can be described as:

$$\Delta T = \frac{\sigma}{\alpha E}\times b \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where ΔT = allowable temperature difference
σ = allowable thermal stress, kg/sq.mm
α = coefficient of thermal expansion, per °C.
E = Young's modulus, kg/sq.mm
b = function of the geometry of the structure
(See Table II for the values of ΔT for some materials.)

An example of such a stationary system is a double pipe heat exchanger with, for instance, both pipes of similar



1—*Double pipe heat exchanger*

materials (*see* Fig. 1). In this case the maximum allowable temperature difference will be:

$$\Delta T = \frac{\sigma}{\alpha E} \times \frac{F_1 + F_2}{F_2} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

with F_1 and F_2 as the surfaces of the cross-sections of the inner and outer tubes respectively.

(ii) *Stationary (time independent) temperature gradient* dT/dx
This gradient is caused by a heat flow per unit area through the material with a heat conductivity coefficient ϕ_w''

$$dT/dx = \frac{1}{\lambda}\phi_w'' \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

(iii) *Unsteady (time dependent) heat flow*
The Fourier equation for heat conduction reads

$$\frac{\delta^2 T}{\delta x^2} = \frac{\lambda}{\rho c} \frac{\delta T}{\delta t} \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

Integration and approximation in a specific case result in

$$\Delta T = f \sqrt{\frac{\rho c}{\lambda}} \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

where f = a constant, describing the geometry and the time function
$\frac{\lambda}{\rho c}$ = a constant, describing the material of construction
ρ = density
c = specific heat
ρc = heat capacity per unit volume.

Elimination of ΔT from equations (1) and (5) gives

$$W = \frac{\sigma}{\alpha E} \sqrt{\frac{\lambda}{\rho c}} \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where W is the temperature shock function of Winkelmann and Schott, sometimes used to correlate the thermal shock resistance of ceramics.

(iv) *Sudden contact between two bodies with different temperatures*
Two bodies a and b with temperatures T_a and T_b will have a contact temperature at the instant of contact T_c, defined by the relation

$$\frac{T_a - T_c}{T_c - T_b} = \sqrt{\frac{(\lambda\rho c)_b}{(\lambda\rho c)_a}} \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

Although the above formulae are based on non-realistic assumptions and are therefore not suitable for calculation of the allowable heat load, the functions described are involved. A comparison of these functions for various materials is shown in Table II.

Table II

Thermal load parameters for various materials

	$\sigma/\alpha E$ (°C.)	λ (kW/m°C.)	$\lambda/\rho c$ (m²/sec)	$\lambda\rho c$ $\left(\left[\frac{kJ}{m^2°C.}\right]^2 sec^{-1}\right)$
Aluminium, 99·8%	15	0·2	$8·3 \times 10^{-5}$	486
Aluminium–3% Mg	62	0·145	$6·1 \times 10^{-5}$	345
Mild steel	85	0·05	$1·38 \times 10^{-5}$	180
Stainless steel	81	0·014	$0·36 \times 10^{-5}$	55

(*d*) *Influence of cracks*

Various laboratory experiments show that aluminium is less susceptible than constructional steel to internal cracks and flaws and behaves like a fully ductile material, with no tendency for brittle fracture at temperatures as low as −196°C. This could mean that plastic deformation at, say, 1,000 load cycles can be supported, whereas for steel this is not so.

The observations in the foregoing paragraphs give a basis for the following comments: For soft aluminium with a large difference between the proof stress and the ultimate tensile strength, the allowable stresses in chemical equipment will at least be defined similar to those of mild steel, *e.g.*, about $\frac{2}{3}$ the 0·2% proof stress. For materials in the hardened state, with a smaller difference between the proof stress and the ultimate tensile strength, the allowable stress should be half of the proof stress or even less, depending on the situation. The allowable stresses in, for instance, the ASME "Boiler and Pressure Vessel Code for Unfired Pressure Vessels" vary from $\frac{2}{3}$ the 0·2% proof stress for the soft materials to as low as 0·3 of the 0·2% proof stress for harder materials, whereas the (tentative) API "Specification for Welded Aluminium-Alloy Storage Tanks" allows 0·80–0·2 of the 0·2% proof stress, depending on the alloy used.[9,14] Owing especially to the low tendency for brittle fracture, it is possible that the allowable stress in pressure vessels could be higher than the general value of $\frac{2}{3}$ the 0·2% proof stress. The authors consider that the tendency to brittle fracture in load cycles of aluminium containing flaws is so important that a study with various alloys is warranted. These tests could enable the designer to determine a safe allowable stress as a function of temperature and the number of load cycles.

Welded aluminium

The considerations for unwelded material form the basis for the allowable stresses of welded aluminium. The properties of welded joints have already been discussed, both for non-heat-treatable and heat-treatable materials. In a welded joint, three types of materials can thus be distinguished: the parent material, the heat-affected zone and the welding bead itself.

Non-heat-treatable type

The properties of the weld itself are normally equal to those of cast aluminium of corresponding composition and are generally not affected by small irregularities; the properties of the softened zones are those of more or less fully-annealed parent material, dependent on the welding procedure. The strength of the welded joint will therefore be substantially the strength of the parent material in the soft quality multiplied by the joint efficiency. If the parent material is in the annealed state the strength of the weld will equal the strength of the parent material times the joint efficiency.

Heat-treatable alloys

The weld bead itself has a cast structure. The zone alongside the welding seams will therefore lose strength, because of the applied heat-treatment, and the strength in these zones will lie between the original value and the strength of the softened material.

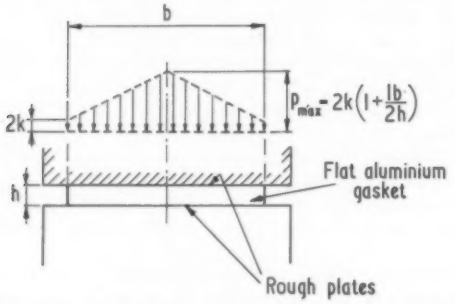
The joint efficiency permitted in, for example, the ASME Boiler Code ranges from as low as 50% to 95%, depending on the type of joint and the testing procedure.[9]

The joint efficiency in the API Specification ranges from 0·75 to 0·85.[14] When the material is used in the hard or half-hard condition the welded joints will become the weak parts of the construction. In many cases, however, the welded joints can be placed in less heavily loaded regions, so that they will not substantially reduce the strength of the equipment.

If a welded joint in a hard material is fully loaded transversely, then the allowable stress of this joint will certainly be lower than that of the parent material; two considerations, however, are worth mentioning:

(*a*) If, for example, a pressure vessel in cold-worked aluminium is loaded to the allowable stress of the parent material, some (soft) welded joints will be stressed somewhat over the 0·2% proof stress and will therefore be strained and so reinforced. The authors consider it to be worthwhile to verify this point through experiments.

(*b*) A very narrow soft zone, *e.g.*, for ½ of the plate thickness, a stress distribution will occur as shown in Fig. 2 for a gasket. It is unlikely that this principle can be used with existing welding practices.



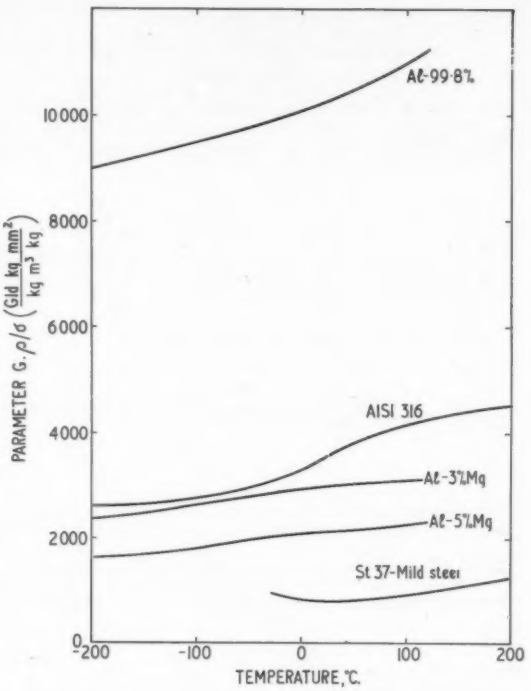
2—*Compression stress distribution on a flat aluminium gasket with width* b, *height* h *and maximum shear stress* k, *compressed between two rough plates*

The need for experiments to determine the allowable stress in a weld, as a function of temperature and number of load cycles, is even more desirable than for unwelded plate as already suggested.

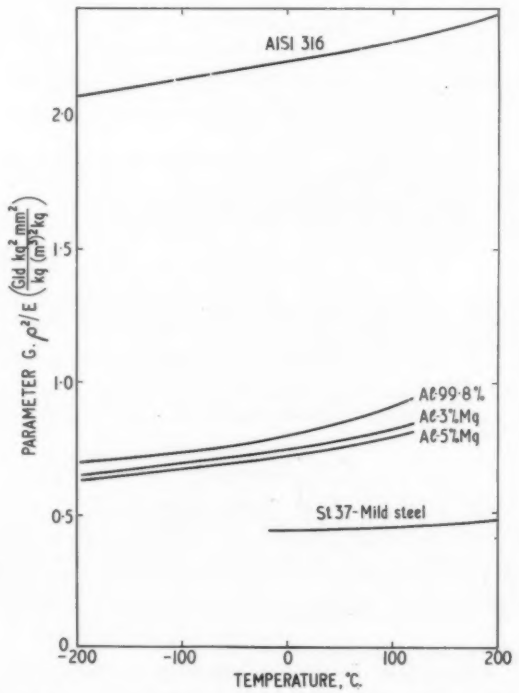
Cost Comparison between Various Aluminium Types, Mild Steel and Stainless Steel

The cost price of chemical equipment constructed in various materials can be compared with the aid of a parameter, which is formed by the cost price per unit material volume of the equipment and by the material criterion, with which, in a given situation the plate thicknesses are defined. For instance:

(i) For equipment where the plate thickness is governed by tensile strength considerations, such as pressure vessels, this parameter will have the form $G\rho/\sigma$.



3—*Price parameter for strength* $G\rho/\sigma$ *for various materials*



4—*Price parameter for stability* $G\rho^2/E$ *for various materials*

(ii) For equipment, where the plate thickness follows from the criterion of stability by its own weight, such as long thin-walled vertical cylinders, this parameter has the form $G\rho^{\frac{1}{3}}/E$,

where G = cost price of the equipment, in gld per kg
ρ = density of the material of construction, kg/cu.m
σ = allowable stress, kg/sq.mm
E = Young's modulus, kg/sq.mm.

In Figs. 3 and 4 these parameters are related to material temperature, for pure aluminium, Al–3% Mg, Al–5% Mg, mild steel (BS.1501–151, Grade A) and stainless steel (18% Cr–8% Ni–2·5% Mo), all materials in the soft condition.

The allowable stresses are taken as $\frac{2}{3}$ the lower yield stress for steel, $\frac{2}{3}$ the 0·2% proof stress for stainless steel, pure aluminium, and Al–3% and Al–5% Mg alloys. For the yield and the 0·2% proof stresses typical figures,[5] not minimum values, were used.

Figure 3 shows clearly that, at room temperature, pressure vessels in Al–3–5% Mg alloy are somewhat cheaper than in stainless steel, but still 3–4 times as expensive as steel pressure vessels. For low-temperature service, equipment in aluminium alloy is cheaper than in stainless steel.

If chemical pressure equipment has to be constructed in pure aluminium, then it will be several times more expensive than in steel, owing to the low permissible stresses for pure aluminium in the soft quality; for this reason, for instance, Al–5% Mg alloy lined with pure aluminium could be used.

Figure 4 shows the cost parameter, where the equipment plate thickness is governed by self-weight stability considerations. Under these circumstances aluminium equipment is 1·8 times more expensive than steel, but several times cheaper than stainless steel equipment.

It should be noted that the information in Figs. 3 and 4 is not based on experience of fabrication in aluminium; it might be expected therefore that many differences in fabrication between steel or stainless steel and aluminium equipment—for example the possible use of complicated extruded profiles or the use of cast equipment parts—have had no influence on the cost price value G. In specific cases, consequently, these cost-figures could be substantially lower for aluminium.

Details of Design

Since the use of chemical equipment in aluminium is now developing, the design will generally be 'translated' from that of steel or stainless steel equipment. Aluminium, however, has properties (*e.g.*, low modulus of elasticity and easy deformability) which differ quantitatively so much from those of steel or stainless steel, that an entirely different approach is needed.

The more important properties of aluminium, with respect to equipment design and fabrication, are:

(*a*) Aluminium is easily deformable, especially at elevated temperatures; aluminium therefore can be extruded to very complicated profiles, at low cost. (*See* Fig. 5, where an extruded profile is depicted as part of a flat tankwall, which is carrying a hydrostatic load. Note the backing piece, which is part of the profiles and suits the butt-welding of two profiles. See also Fig. 6, where an extruded traced tube is shown)

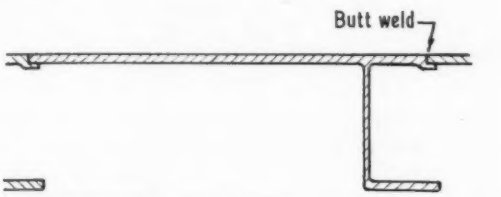
(*b*) Several suitable aluminium types for chemical equipment can be cast and the cast component can be welded onto plates and profiles

(*c*) The welding of half-hard aluminium generally causes a cast structure in the weld and more or less fully annealed zones between the welds and the parent material. The welds should therefore be positioned in less heavily loaded regions

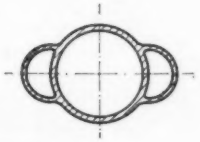
(*d*) The machining of aluminium is easy and cheap; special machined parts do not increase the equipment costs too much

(*e*) Owing to the low modulus of elasticity (Young's Modulus) aluminium will absorb much work, which is normally an advantage for aluminium equipment, but which causes some complications in the forming of parts such as discs. This characteristic, however, makes aluminium unstable in compression and buckling might occur. If, on the other hand, the compression stresses are caused by the self-weight of the equipment, aluminium has about the same tendency for instability in compression as steel, for the ratio density/elastic-modulus is about the same for both materials, compared on a basis of equal wall thickness

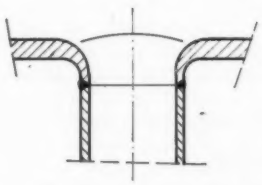
(*f*) The impact strength of aluminium alloy is rather low, normally about 3–5 kg/sq.cm at room temperature[3,4]



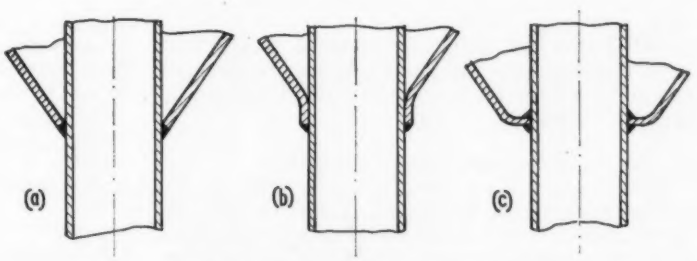
5—*Typical butt welded extruded profile for aluminium*



6—*Typical aluminium traced (heated or cooled) pipe*



7—*Tube joint with weld in region of low stress*



8—*Typical connection of a tube to a conical bottom*: (a) *Steel*; (b) *and* (c) *aluminium*

(*g*) Many aluminium alloys are relatively sensitive to notches, which is especially important where fluctuating stresses are expected. For this reason sudden changes in cross-section, and even scratches transverse to the loading stresses, should be avoided[4]

(*h*) Aluminium is very sensitive to contamination with, for instance, heavy metals; this implies thorough cleanliness during fabrication of aluminium equipment, to avoid traces of steel, lead, copper, etc. on the equipment surface, for these metal traces will cause chemical attack as a result of the low electrolytic potential of aluminium, as soon as an electrolyte is present. This low electrolytic potential of aluminium to most materials of construction makes complete insulation from structural parts of, for instance, steel or copper, necessary.

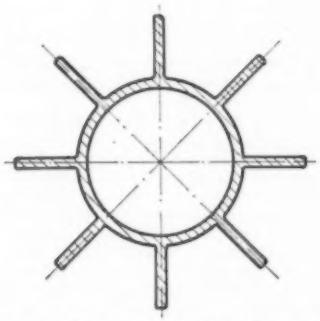
Some design details are shown in Figs. 7 and 8. In Fig. 7 the weld is situated in a less heavily loaded region and no notch is formed. In Fig. 8*a* a tube is welded in a conical bottom in the same way as it is normally done for steel; in Figs. 8*b* and 8*c* welded joints more suitable for aluminium are shown; Fig. 8*b* has still a notch and could moreover suffer from crevice corrosion in the tapered annular crevice; therefore the detail in Fig. 8*c* is preferred.

Typical Equipment Designs and Constructions in Aluminium

A number of typical applications of aluminium in the chemical industry will be discussed, on the basis of the properties of the material.

Plastic deformation at low stresses

Heat-treatable and non-heat-treatable aluminium types can be extruded at elevated temperatures to



9—*Extruded aluminium heat-exchanger tube*

profiles of very complicated forms, like heat-exchanger tubes with integrated fins (Fig. 9).

The ductility of aluminium makes it an excellent material for gaskets. The guiding principle is the high compression stress that can be safely used, as will be explained below.

(*a*) *Flat aluminium gasket under compression*

This gasket is by no means a new idea, but its advantages are little recognised as it is not sold by gasket manufacturers and is therefore not advertised. Also, the formulae for load distribution are not given in the technical handbooks. Therefore it seems in order to start with a few remarks on the compression of a flat ductile plate between two rough plates. This subject has been treated by Hill and others.[10]

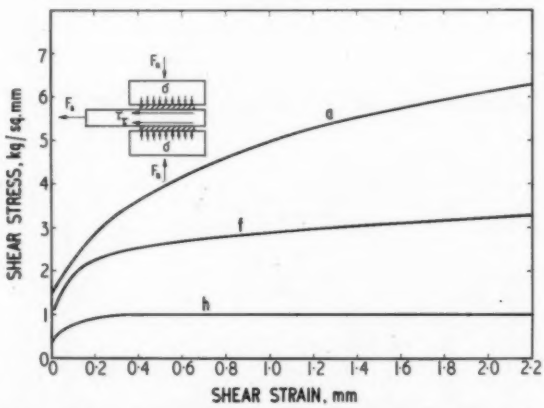
Some simplifying assumptions will be made (Fig. 2). The deformation is plastic only and with a constant maximum shear stress k; elastic deformation will be neglected. The gasket will be pressed between two rough plates, assumed to be grooved so that the gasket cannot move horizontally as such, horizontal moment will entail horizontal shear in the gasket in the region close to the rough plates.

It can be calculated[11] that the compression stress b on the gasket will be $2k$ on the edges and $2k\,(1+\frac{1}{2}\,b/h)$ in the centre. Therefore a gasket with a width/height ratio $\frac{b}{h}=10$ will have a central compression stress of $p_{max}=2k(1+5)=12k$ and an average compression stress of $p_{av}=7k$. However, when the surfaces of the plates are ideally smooth, no friction between the gasket and the plates will exist and the compression stress would be constant over the gasket surface, equal to $p=2k$.

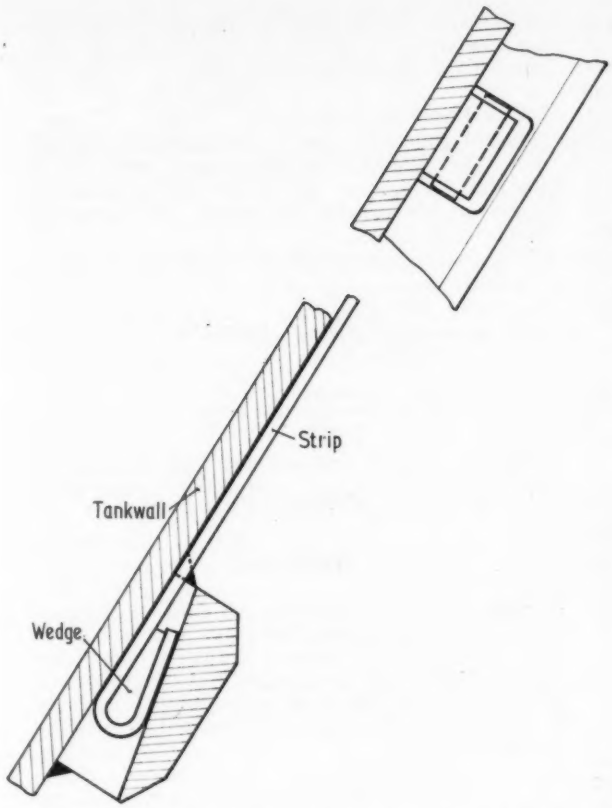
The performance of a gasket can now be explained as follows: firstly the gasket will touch the two flanges (rough plates) at a few points. Tightening the flange bolts will compress the gasket into the grooves of the flange. Initially a low compression stress is required, say $2k$, equal to the stress for plastic deformation in uniaxial stress. As the grooves fill up, the compression stress increases and horizontal flow will start, increasing b and decreasing h. At a certain average compression stress p_{av}, equilibrium will be reached. It could be assumed that at this equilibrium pressure the width b might be larger than the width of the flange, causing the gasket to be extruded out of the flange. This phenomenon would stop before complete blow-out, as $h=0$ would entail infinite compression stress. This argument may prove that overloading a flat metal gasket is not possible. Moreover, work hardening of aluminium increases the shear stress k considerably, making excessive gasket flow unlikely.

(*b*) *Flat aluminium gasket under compression and shear*

A gasket between two unsymmetrical flanges will also be loaded with a horizontal shear force, as the radial deformation of the flanges, due to pressure and



10—*Shear stress as a function of shear strain of a 1 mm soft aluminium gasket. The curves* (a), (f) *and* (h) *are for a compression stress on the gasket of 25, 7·5 and 2·5 kg/sq.mm respectively*



temperature changes, is not equal. This effect has been tested by the authors on many samples of aluminium and silver.[12] Repeated radial shear strain under constant compression stress caused considerable thinning of the gasket, sometimes a reduction in height to $\frac{1}{3}$ of the initial value. Cracking of the gasket did not occur, which can be understood as no tensile stress occurs under this type of loading. Figure 10 shows the shear stress as a function of the shear strain for a typical case.

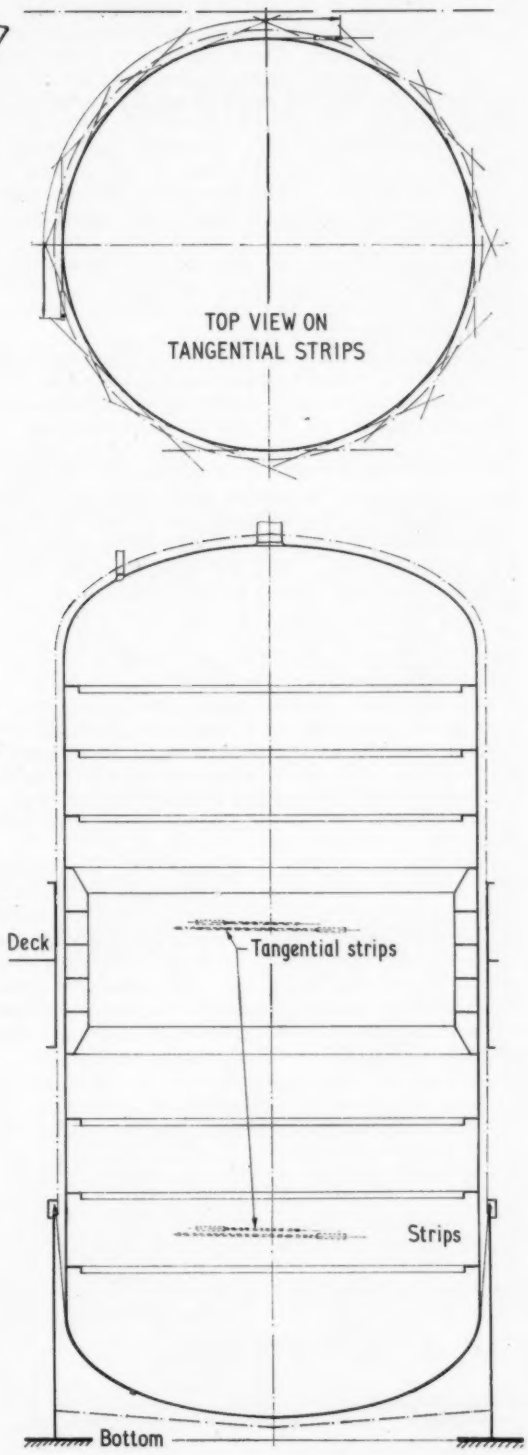
Work hardening is clearly shown in case (*a*); in case (*h*) there is little increase of shear stress with shear strain and it was observed that the gasket slipped relative to the flange as the compression stress was low.

Ductility at low temperatures

Various aluminium types, *e.g.*, Al–3–5% Mg alloys, have impact values which, although rather low at room temperature, are not liable to show a sharp break down, as does normal mild steel at temperatures around 0°C. This property suggests that these materials are suitable for low-temperature applications, which has been confirmed by a number of recent tests[8] which show that even thick plates are still ductile at temperatures of −196°C.

For the transport of liquefied gases, like natural gas at −155°C., a number of designs of aluminium tanks for seagoing tankships have been proposed.[13]

The Technological University of Delft, Holland,



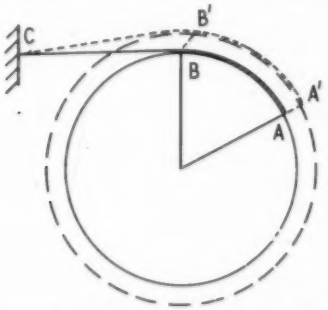
11—*Design study of a container for a liquefied methane tanker*

also made a study of seagoing liquefied natural gas carriers. This study resulted in a preliminary design of a transporter, equipped with vertical cylindrical tanks in Al–5% Mg alloy. These tanks have dimensions which depend on their place in the ship; the biggest has a diameter of 11·16 m (37 ft) and a total height of 23·65 m (78 ft).

The tanks consist of a cylindrical shell of plate thickness varying from 15 mm ($\frac{5}{8}$ in.) bottom to 10 mm ($\frac{3}{8}$ in.) top reinforced with stiffening rings, and are closed by elliptical heads of 17 mm ($\frac{11}{16}$ in.) wall thickness (bottom) 10 mm ($\frac{3}{8}$ in.) top. Apart from vertical loading by gravity, the tanks should withstand loading due to a maximum inclination of 30° of the ship and an acceleration due to pitching, heaving, and rolling of 0·4 g (*see* Fig. 11).

The tanks are insulated with at least 250 mm (10 in.) of rockwool or foamed plastic, dependent on the value of the natural gas and on the way in which the boiled-off-gas is disposed of. The tank is supported near its bottom by a large number of vertical Ni-steel strips, which are attached to a skirt placed on the ship's bottom. The lateral support is given in the upper part by means of two sets of tangential strips, which are fastened to the reinforced deck construction of the ship, and at the bottom by two similar sets. These strips cater for the forces caused by the inclination and the rolling movement of the ship. The strips are fastened to the tankwall by folding the ends around a small wedge and by fitting the now tapered ends in a tapered holder, welded onto the tankwall, as is shown in Fig. 11. At the other end, the strip passes through a gas-tight joint in the insulation-cover and has a threaded end which is fastened to the ship structure. The tankwall is reinforced at the place where the tangential strips are attached by stiffeners and by a double wall with a high resistance against bending because of its box form.

The design of the tangential strip-supporting system is such that temperature changes in the tanks will not influence the tension of the strips, as shown in Fig. 12. This method of supporting the tanks has the advantage that the support forces are equally divided, so that the stresses in the tankwall, caused by these forces, are low, and that the support is elastic and that the heat flow through the long strips is low. Its disadvantage is that the installation must be accurate.



12—*Lateral support of the container. The supporting strip* ABC *is in contact with the container over the arc* AB. *At increasing temperature* A *will move to* A′, B *will move to* B′ *as the coefficient of thermal expansion of the strip is lower than that of the tank. The movement of* B *to* B′ *can compensate the thermal expansion of* CB. (*Patent applied for*)

The tanks are designed in accordance with the requirements of the U.S. Coast Guard and the API–ASME Unfired Pressure Vessels Code.

High strength/density ratios

The use of aluminium in the chemical industry, where the allowable strength/density ratio σ/ρ is important, applies not only in the field of transport equipment, but also for instance for ultra-centrifuge rotors.

The stresses in a centrifuge rotor are governed by

$$v^2 = \frac{\sigma}{\rho} \times h$$

where v = tangential velocity, m/sec
$\sigma = N/m^2$
ρ = kg/cu.m
h = geometry factor
(for a thinwalled tube $h = 1$;
(for a constant stress disc $h < 1$)

For this purpose heat-treatable high-strength Al–Zn–Mg–Cu alloy[4] is used, with a 0·2% proof stress of 50–60 kg/sq.mm (5×10^8–6×10^8 N/m^2).

Conclusions

Many good reasons exist for making chemical equipment in aluminium, but experience in a broad field is still lacking. For the designs of aluminium equipment an 'aluminium minded' attitude is necessary, for the specific properties of this material do not make it suitable for handling and treatment as steel or stainless steel.

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UTRECHT MEETING, 1961

Aluminium Welding Practice

By L. Capel

The paper considers the factors that affect the quality of welds in aluminium, made by the inert-gas metal-arc and tungsten-argonarc processes. Suitable edge preparations are illustrated, and formulae are given from which distortion can be calculated. Types of welding equipment are described and their chief characteristics are outlined.

Considerable attention is given to the examination of welds by non-destructive methods, and detailed recommendations are given for radiographic methods.

Edge Preparations

THERE are two principal welding processes available for the fabrication of aluminium and its alloys, which make it possible to attain the high standard required by the chemical and nuclear energy industries. These are the inert-gas-tungsten-arc (Tig) and the inert-gas-metal-arc (Mig) processes.

Although each of these have particular applications the best results are generally obtained when the edge preparations shown in Fig. 1 are used; these diagrams are based on data used in the production of high-quality welded work, for which complete X-ray inspection is required.

The following points influence the shape of the edge preparation:

(*a*) The thickness of the root face is governed by the choice of welding process

(*b*) A sound even root penetration can be achieved only by the use of the tungsten-arc process

This is important in the welding of small diameter pipes, where the inner bore cannot be reached. In this case the thickness of the root face is 1·2–2 mm. However, if the Mig process is used, the root face must be larger (about 3 mm) so as to contain the very intense arc and to prevent excessive and irregular penetration; in most cases root machining would be necessary but this is an expensive and often impracticable operation

(*c*) The included angle and the total width of the preparation are related to the diameter of the torch nozzle, to allow manipulation

(*d*) In the case of large thicknesses, where a sealing run has to be applied, a part of the previously welded root run will have to be chipped out; this relates to the flat part in the case of a double-U groove

(*e*) If much distortion is expected it is recommended that welding should take place alternately on both sides of the joint

(*f*) With welding in the horizontal-vertical position distortion has to be prevented as far as possible. Correct edge preparation and choice of welding process are of great importance

(*g*) Double-operator vertical welding offers advantages with the edge preparation shown in Fig. 1 and results in a welded joint which can comply with nearly every requirement.

Double grooves which have to be welded on both sides must be back-chipped with great care before welding takes place on the second side. Special circular-shaped chisels, in the hands of a skilled operator, are necessary to obtain a smoothly shaped groove.

For preparing welding edges, various machines are available which produce a smooth welding edge, complying with the dimensions specified. For long plate edges planing or milling may be applied; the clamping of the work piece has to be effected with great care, so that it remains flat during machining.

The cutting speed, depth, and feed differ for the various alloys, which may be divided in three groups:

(i) Non-heat-treatable alloys
(ii) Heat-treatable alloys
(iii) Alloys with a high silicon content.

Some examples of machined welding edges are shown in Fig. 2.

As shown in Fig. 2*d* it is sometimes required to prepare the welding groove entirely by hand as, for example, in the attachment of a 16in. nozzle to a 24 in. pipe. With the aid of a template, the parts are made to fit exactly with the correct groove profile to obtain good root penetration.

Distortion

Various investigators have tried to prepare formulae for the calculation of the shrinkage of welded seams. In a formula produced by Gilde[1] the influence of welding current, arc voltage, welding speed and physical properties of the material has been evaluated, so that a more accurate prediction of shrinkage may be obtained.

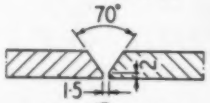
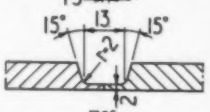
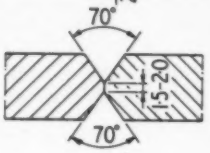
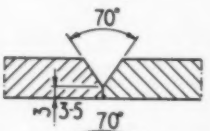
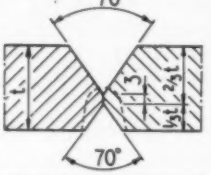
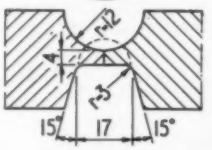
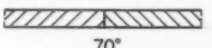
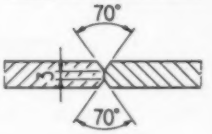
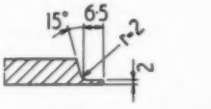
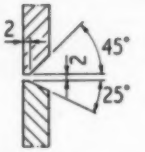
A comparison has been made between the shrinkage of corresponding welded seams in aluminium, stainless steel, and carbon steel. The shrinkages found in practice were compared with those calculated from Gilde's work, using the formula:

$$\Delta l = \frac{0{\cdot}24 \times 6000.\ K.\ \alpha \times V.I.a}{s.u.\lambda}$$

relating to a measured length of 100 mm.

The symbols and their values for aluminium,

Manuscript received 20th March, 1961
The author is at Werkspoor N.V., Utrecht, Netherlands.

Object to be Welded	*Welding Method*	*Joint Preparation*
Downhand Welding		
Plate thickness 3–5 mm Welded from one side	Tig	
Plate thickness 5–10 mm Welded from one side	Tig	
Plate thickness 5–10 mm Welded from one side Good penetration	Tig	
Plate thickness 10–25 mm Welded from both sides	Tig	
Plate thickness 6–15 mm Machined side welded first. Back chipping and weld finished	Mig	
Plate thickness 12–30 mm Welded from wide side. Rootpass chipped out and weld finished	Mig	
Plate thickness over 25 mm Welded from upper side. Root pass chipped out and weld finished	Mig	
Vertical Upwards Welding		
Plate thickness 5–6 mm Performed with two welders	Tig	
Plate thickness 6–9 mm Performed with two welders	Tig	
Fillet Butt Weld Plate thickness 3–10 mm	Tig Mig	
Pipewelding Circumferential seams in pipes from 2–6 in. dia.	Tig	
Horizontal-Vertical Welding Plate thickness 6–9 mm	Tig	

1—*Edge preparations for inert-gas metal-arc welding of aluminium*

(a)

(b)

(c)

2a–c—*Machined welding edges in aluminium alloys*

stainless steel, and carbon steel respectively are given in Table I.

Two plates 6 mm thick, having a length of 500 mm and a width of 150 mm in aluminium, stainless steel, and carbon steel were welded. The edge preparation was a 60° V-groove, without root gap. Precautions were taken to prevent angular distortion and heat losses were limited by asbestos insulation.

The aluminium plates were welded by the Tig process, whereas both the stainless steel and the carbon steel plates were welded with covered electrodes.

2d—Edge preparation for branch connection

The following data were obtained:

	Aluminium	*Stainless Steel*	*Carbon Steel*
First layer:			
$V \times I$ (Watts)	4050	2320	2100
s (Layer thickness, mm)	3·6	3·4	3·7
u (Welding speed, cm.min^{-1})	9	19	20
Final layer:			
$V \times I$	4050	2550	2100
s	5·6	2·6	2·3
u	9·2	18	22

Welding conditions:

Aluminium —1st layer: filler rod dia. 3 mm; electrode dia. $\frac{1}{16}$ in.; gas flow 8 l/min.
2nd layer: filler rod dia. 4 mm; electrode dia. $\frac{1}{16}$ in.; gas flow 8 l/min.

Stainless steel—1st layer: electrode dia. 2·5 mm
2nd layer: electrode dia. 3·25 mm

Carbon steel —1st layer: electrode dia. 2·5 mm
2nd layer: electrode dia. 3·25 mm

Measurements were made of the transverse shrinkage of the weld after completion of each layer at three places alongside the weld, as well as the decrease in the width of each plate and the overall reduction in width of the workpiece (see Figs. 3*a* and *b*).

To carry out the calculation as accurately as possible, it was necessary to know the value of the factor K (the efficiency of the welding arc) especially as different welding methods were applied. Based on repeated measurements the following values were determined:

Aluminium —K=0·35
Stainless steel—K=0·75
Carbon steel —K=0·88

The low value for the Tig welding of aluminium in relation to that for the covered electrodes is due to a larger radiation loss and to the heat absorbed by the gas shield.

Substitution of the known values in Gilde's formula gives the following relationship:

$$\Delta l \text{ (aluminium)} = \frac{20{\cdot}4 \,.\, W \,.\, 10^3}{s.u.}$$

$$\Delta l \text{ (stainless steel)} = \frac{22{\cdot}7 \,.\, W \,.\, 10^3}{s.u.}$$

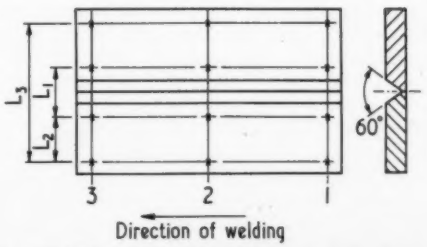
$$\Delta l \text{ (carbon steel)} = \frac{17{\cdot}4 \,.\, W \,.\, 10^3}{s.u.}$$

where $W = V \times I$ (watts)

Table I

Symbols and values for shrinkage formula

	Aluminium	*Stainless Steel*	*Carbon Steel*
a=Temperature conductivity, cm^2.sec	0·870	0·047	0·126
λ=Heat conductivity, cal.cm^{-1}.sec^{-1}. °C^{-1}	0·55	0·045	0·11
K=Efficiency of welding arc in terms of heat input to parent metal			
I=Welding current, amp			
V=Arc voltage V			
s=Thickness of layer of weld metal, mm			
α=Linear coefficient of expansion °C^{-1}	25·6	20	12
The following data are also necessary:			
t=Time, sec			
γ=Specific gravity, g.cm^{-3}	2·75	7·9	7·8
l=Measured length, mm			
G=Weight of plate, kg			
b=Length of plate, cm			
c=Specific heat, cal.g^{-1} °C^{-1}	0·23	0·12	0·112
u=Welding speed, cm.min^{-1}			



3a—Welded test plate for shrinkage measurements

3b—Plate used for shrinkage measurements

Table II

Measured shrinkage values

		Aluminium, mm		*Stainless steel, mm*		*Carbon steel, mm*	
		Δl_1	Δl_2	Δl_1	Δl_2	Δl_1	Δl_2
L_1	1.	−1·0	−0·4	−0·3	−0·9	−0·2	−0·6
	2.	−2·2	−1·1	−0·8	−1·6	−0·4	−0·9
	3.	−1·5	−1·3	−0·4	−1·1	−0·4	−0·9
L_2	1.	−0·1	−0·1	−0·2	−0·4	0	0
	2.	−0·1	−0·1	−0·1	−0·2	0	−0·2
	3.	−0·1	−0·1	−0·1	−0·1	0	−0·2
L_3	1.	−0·6	−0·5	−0·5	−1·2	−0·2	−0·6
	2.	−1·8	−1·3	−0·2	−1·0	−0·5	−1·5
	3.	−1·7	−1·4	−0·6	−1·0	−0·4	−1·2

A comparison between the actual measurements and the calculated shrinkage is as follows:

		Δl_1 *measured, mm*	Δl_2 *calculated, mm*
Aluminium:	1st layer	−2·2	−2·5
	2nd layer	−1·1	−1·6
Stainless steel:	1st layer	−0·8	−0·8
	2nd layer	−1·6	−1·2
Carbon steel:	1st layer	−0·4	−0·5
	2nd layer	−0·9	−0·7

The various shrinkage values measured on the different plates are given in Table II. From these values it may be concluded that the large shrinkage of aluminium is mainly caused by the low welding speed in comparison with that of the covered electrodes.

The relatively large heat input is compensated by the low K value, so that there is little difference in the usefully applied heat. The high value of the temperature conductivity, *i.e.*, a measure of the travel speed of an isotherm, may explain the low welding speed. Moreover it proves that a (small) shrinkage occurs in the plate by heating it.

The impression is obtained from this investigation that, with stainless steel and to a lesser extent with carbon steel, the shrinkage is limited to the seam and its close surroundings. This may be an explanation for the smaller deformation that occurs during the welding of stainless and carbon steels which has also been found in practice.

When the measured results are compared with those found by calculation a correlation is obtained within certain limits, so that the formula will give a reasonable prediction of the shrinkage to be expected.

Only the values measured in the centre of the work piece are comparable because it is only here that the welding conditions are in balance; the heat flow is not limited to one direction as it is at the beginning and the end of the weld.

However, some methods can be mentioned by which the shrinkage may be limited; for example, the use of high welding speed and a high energy input for comparable quantities of deposited metal. The investigation indicates advantages for the Mig welding process. As in the case of other materials the welding of aluminium requires special precautions to limit the shrinkage, *e.g.*, clamped welding, close joint welding, or a welding method by which symmetrical shrinkage occurs (*e.g.*, double-operator vertical welding).

Inert-Gas Metal-Arc Welding Equipment

Welding equipment has to comply with many requirements, but after various investigations and measurements it has proved possible to analyse several factors which influence the operation of the welding process.

The welding equipment normally comprises a welding transformer, an arc stabiliser, cables and a torch and, in some cases a d.c. suppressor.

Transformer

The welding current is obtained from the a.c. mains supply through a welding transformer. This transformer must have, for tungsten-arc welding, a higher duty cycle, for changing of electrodes does not occur. Some characteristics, such as arc stability, tendency to extinguish the arc, arc noise, and tendency to spattering may influence the qualification of the transformer. It is our impression that, in principle, these characteristics do not directly influence the heat capacity of the welding arc, but that they govern the ease with which welding takes place. An effective method for checking these characteristics is not known and is still a subject of research. However, in the meantime, it is recommended that the transformer be considered only as a source of energy and that an improvement in the characteristics should be attempted by means of auxiliary equipment.

From observations during welding it has been determined that:

(i) A 10% variation in the primary voltage of the mains does not cause trouble
(ii) An open-circuit voltage less than 50 V has an unfavourable influence on the stability of the arc. (The arc voltage normally is 22–25 V)
(iii) The phase-shift between current and voltage on the secondary side is difficult to determine and is probably not important for the welding process. The phase-shift in the primary side is not important
(iv) There is a relationship between the dynamic characteristics of the transformer and the quality of the welding arc; this is a subject which is under research at present.

A fact which has come to light during this investigation is that an induced voltage of 140 V and higher can occur when the polarity of the electrode is changed from negative to positive. Often it is possible to make use of this feature, for it provides increased stabilisation. However, the effect is not reproducible and it is not therefore advisable to rely on it; proper auxiliary equipment is required.

Arc stabiliser

By the application of a stabiliser it is possible to strike the arc and to keep it burning without touching the parent metal. It causes ionisation of the arc gap so that restriking is possible, and it should also have sufficient energy to initiate thermal emission.

The two main methods of arc stabilisation are:

(i) The h.f. spark unit by which a high-frequency discharge is superimposed on the welding current
(ii) The surge injector unit; a short impulse (10–300 μsec) with an amplitude of 200–400 V is superimposed on the welding voltage during the zero-passage of current.

Arc re-ignition is more precise with the surge-injector than with the h.f. unit. It has been clearly

shown that in the latter the discharge of the spark should take place at the exact moment when polarity of the welding voltage is changing. This is attained by connecting the welding transformer to two phases of the alternating current mains and connecting the h.f. unit to the third phase and to neutral.

The spark length must be at least 2–4 mm with the transformer switched off. A longer spark length indicates that the equipment is not properly adjusted, so that the energy of the discharge decreases.

The surge unit injects on the welding voltage an impulse which has sufficient tension to initiate reionisation and moreover to put such a quantity of energy into the arc that thermal emission may start.

The more definite character of this impulse is a great advantage in comparison with h.f. stabilisation. Based on measurements it has been shown that in stabilisation by surge injection a single cycle of the welding voltage is missed.

D.C. Suppressor

When welding aluminium by the Tig process a d.c. component arises in addition to the alternating current; the effects of this are:

(i) The d.c. magnetisation of the iron core of the transformer which adversely effects the loading on the machine by the development of extra heat
(ii) A symptom which may be considered as a displacement of the zero-line of the secondary current, such that the positive half-cycles are diminished in value and thus reduce the cleaning effect of the arc.

These effects can be eliminated by a suitable capacitor connected in series with the welding circuit.

It is known that some welders prefer to use a capacitor when putting a root in aluminium tubes, so that excellent root penetration is obtained. The filling of the remainder of the joint can then be executed without the capacitor. This is probably due to the elimination of the d.c. component which causes a different heat distribution between electrode, parent metal, and the arc.

Cables and torch

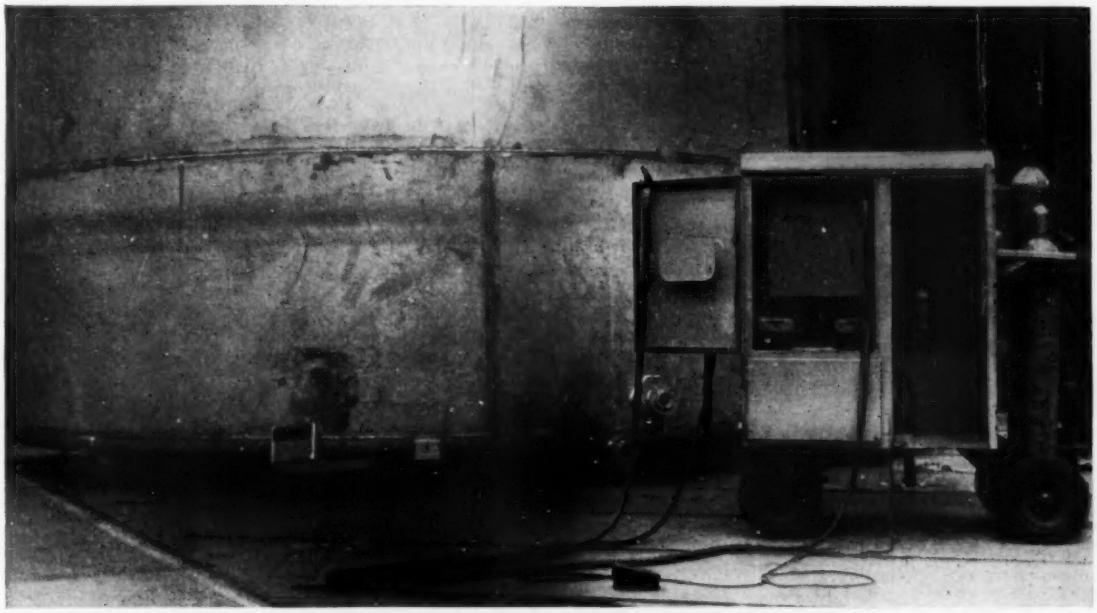
When using stabilising apparatus it is found that h.f. energy may be lost by stray capacity in the water-cooled cable, resulting in arc-extinction and interruptions during welding. In this case good inspection is recommended and particular care has to be taken to ensure that the conductivity of the water is as low as possible.

In brief, the requirements for Tig welding as far as they are known up to now, can be summarised as follows:

(i) The transformer must be capable of working at a sufficiently high duty cycle
(ii) The dynamic characteristics of the transformer are important. It may be that in future these characteristics can be determined numerically
(iii) The arc-stabiliser has to stabilise the welding current completely; in other words no interruptions longer than the duration of a half-cycle may occur. The stabiliser must not interfere with radio or T.V.
(iv) At the choice of the welder, a d.c. suppressor can be fitted
(v) Cooling has to take place by means of fresh water. In case of trouble check whether the cooling water is dissipating h.f. energy by temporarily removing the earth-connection. (With impulse stabilisation this check is superfluous (Fig. 4).)

Defects in Welds and Their Repair

For welding aluminium it is recommended that the conditions be chosen to ensure a minimum possibility of making defects. The following points are of particular importance:



4—Welding set for tungsten-inert-gas welding of aluminium

(*a*) By paying attention to the position and the accessibility of the joint to be welded during the planning of the job a lot of trouble in fabrication may be avoided

(*b*) The welding edge must be accurately prepared and the seam must be assembled exactly in line. If preheating is necessary precautions must be taken to ensure that the seam does not show any deviation.

The root face of U-groove welds in pipes requires great care in fitting, so that a smooth root penetration is obtained

(*c*) The choice of filler rod is governed among other factors by:
- (i) The requirements for the mechanical properties of the joint
- (ii) The requirements for the corrosion resistance of the joint
- (iii) The surface finish of the completed weld

(*d*) If preheating is necessary electric heating is preferable, although in practice this is difficult to apply. In most cases, propane burners are used and continuous checking of the temperature is necessary by special temperature-indicating crayons; the indication marks should be made some distance from the weld

(*e*) The condition of the welding plant must be satisfactory. Special attention should be given to: the connections of the hoses, so that no leakage can occur; sufficient cooling of the torch; the condition of the tungsten-electrode and the gas nozzle. It is also important that the argon gas is dry and of high purity

(*f*) The electrical apparatus must also be correctly adjusted so as to give: correct spark length of the h.f. unit with disconnected transformer; correct connections of current and earth lead; correct phase difference between h.f. discharge and welding voltage; correct size of the tungsten-electrode for the current to be used

(*g*) Immediately before welding, the welding edges and a strip of the parent metal on both sides of the welding groove must be cleaned, preferably by scraping. The filler wire must be ground. A starting strip for striking the arc is required

(*h*) Tack welds must be carefully made to ensure that they are faultless; any cracks must be carefully chipped out.

In spite of great care in welding, there may be weld defects which may be revealed by radiography or penetrant inspection, *e.g.*:

- (i) Lack of fusion
- (ii) Gas inclusions
- (iii) Cracks
- (iv) Incomplete root penetration
- (v) Oxide inclusions
- (vi) Tungsten inclusions

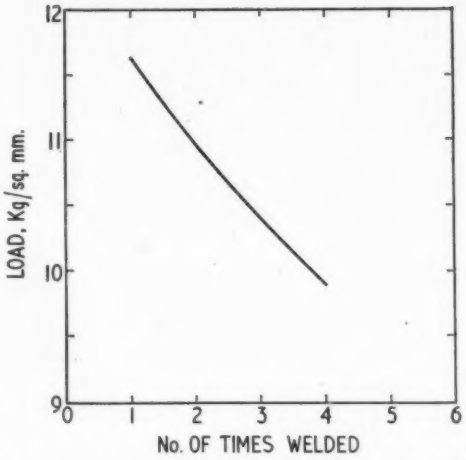
It is our impression that the defects described under (*a*), (*d*), (*e*), and (*f*) are a function of the skill of the welder, whereas the defects mentioned under (*b*), (*c*,) and (*e*) may in addition be due to the quality of the parent and filler metals. The tests described in the next section are of importance for this purpose.

When aluminium welds have to be repaired to remove inadmissible defects, the repair work must be carried out very carefully. Chipping and/or grinding have to be carried out as indicated by the radiograph until the actual defect is found, a regularly bevelled groove must be formed in which rewelding can take place.

In general, especially for aluminium alloys, the mechanical strength in the region of the repair will be diminished. This is shown by the following example.

A 6 in. dia. pipe made of a heat-treatable alloy was welded in the downhand position. Four segments were then chipped out and rewelded with 1, 2, 3, and 4 runs respectively, such that each part had been welded, 1, 2, 3, and 4 times. From each segment two test pieces were made and tested. The following results were obtained:

(i) The number of cracks increased in proportion to the number of runs



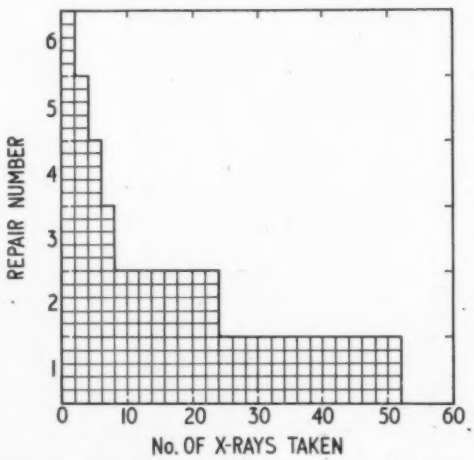
5—Decrease in tensile strength of repaired aluminium weld

(ii) The tensile strength of the welded joint decreased in proportion to the number of runs although an allowable value remained, the fracture occurring alongside the weld (Fig. 5).

	Tensile strength, kg/sq.mm			
Bar	*1 run*	*2 runs*	*3 runs*	*4 runs*
1	11·8	11·1	10·6	9·9
2	11·5	10·9	10·1	9·8

Much trouble can be experienced in the repair of plates which are welded by one or two passes only. As an example, a plate with a thickness of 6 mm is taken to illustrate this problem.

When a severe fault has been found in a weld, relatively deep chipping-out may be necessary. The bottom of the groove for the repair welding is weld metal, and in many cases grain growth will have increased crack sensitivity. Radiographs will show clearly what has happened and in some cases the weld quality will be seen to have diminished. It is then recommended that a portion of the weld seam be removed and replaced



6—Histogram of the possibility of repairing a defect in an aluminium weld

by a piece of the plate material which has been suitably prepared for welding in. Figures from practice show that the number of repairs to a given section of a weld should be limited to three. A chart taken of 100 defective welds is shown in Fig. 6. This shows that the chance of a successful repair after the third repeat is rather poor. One of the causes of this may be that the chipping out and rewelding has extended the width of the weld metal so that any repairs in excess of three are often carried out in a groove formed entirely in weld metal.

Crack Sensitivity of Various Aluminium Alloys

During the welding of aluminium tubes (quality Al–Mg–Si—H9—(AA 6063)), it became clear that cracks occurred in welding the root pass. This gave rise to a more intensive investigation.

In general, 4 in. pipes were considered of quality T4, after which they were heat-treated to obtain the T6 condition.

The quality required for these welds was very high. All welds were subject to X-ray inspection, and the only defect acceptable was a single gashole. In addition the root penetration had to have a regular and smooth appearance.

It had been found that welding aluminium in the horizontal-vertical position was difficult if non-porous welds were required. However, welding pipes that are fixed horizontally is most difficult for the welder, because, to obtain even root penetration on the inside of the pipe, he has to manipulate his torch accurately so as to keep it in a constant relationship with the molten weld pool.

From experience with welding mild and stainless steel piping for high-pressure and temperature service, it is well known that the production of a perfect root pass in a pipe is difficult. Such a perfect root pass is attained only after a long training period, during which the actual working conditions are simulated as closely as possible. Many gas-inclusions were observed in the welds in our early work.

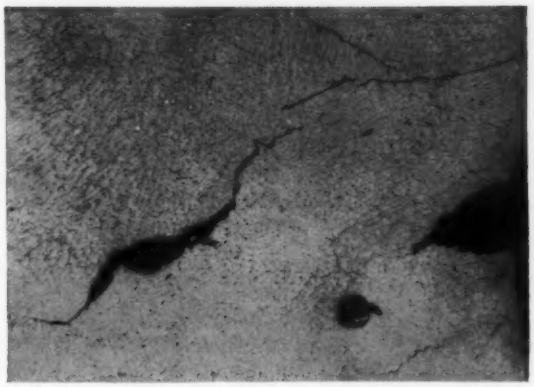
When, by certain procedures, the porosity was reduced to an acceptable level many cracks were found to be present. All root passes were tungsten-arc welded using filler rods of Al–5% Si alloy.

The compositions of the material and filler wire were as follows:

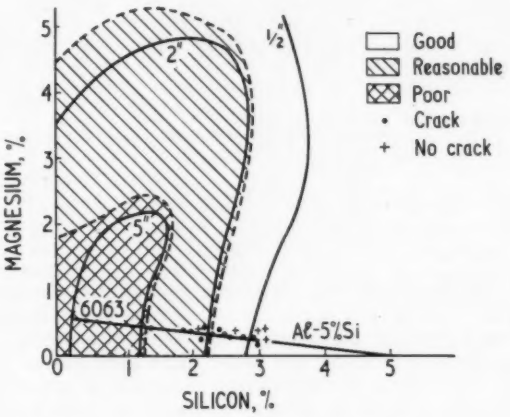
	H9	*H10*	*Al–5%Si*
Mg,%	0·45 – 0·9	0·8 – 1·2	0·05
Si,%	0·2 – 0·6	0·4 – 0·8	4·5 – 6

Very careful inspection of the radiographs, which were made immediately after welding of the root pass, proved that many of these root welds contained one or more small cracks. Often, the percentage of crack-free welds was very low.

From a large series of welding tests 17 were selected for further investigation. It had been shown that small cracks on the inside were not visible on the radiograph but could be observed after sectioning the root pass. The welds were sectioned at places where cracks were indicated and at crack-free places as shown by the radiograph. The sections were then examined microscopically; the percentage dilution was also determined.



7—Deeply penetrating crack in Al–Mg–Si tube weld



8—Crack sensitivity diagram, on which the results of investigations on different welds are marked

Micro-examination showed cracks which, in some cases, penetrated deeply into the weld, as may be seen from Fig. 7. From the dilution determined the Mg and Si contents of the weld metal, which has a homogeneous chemical composition, were calculated.

With the aid of these calculations a curve showing the susceptibility to cracking was drawn (Fig. 8), in which is also indicated whether or not cracks were discovered; the dilution varied from 45% to 79%. The points within the ½ in. curve show the results of ring cracking tests; it should be mentioned that the cracks were very local. From the literature it is known that, in addition to the composition of the weld metal, other factors also influence the formation of a crack. However, from this investigation it is clearly shown that dilution greatly increases the risk of cracking.

Based on the results shown in Fig. 8 it may be concluded that there are two methods which may be employed to obtain an improvement in quality. Firstly, by using filler rods with a higher Si content, so as to give a higher Si content in the weld at the same dilution, and so shifting the position in the diagram to the safer area. The effect of the higher silicon on corrosion resistance should be considered in each case.

Secondly, by obtaining an extremely convex root run which will be composed largely of filler metal. The thickness of the root face should be reduced as far as possible. These modifications result in a root

9—Root runs in an aluminium pipe weld

run shape *A* as compared with the original shape *B* (Fig. 9).

With shape *A* the Al–5% Si filler metal may be retained, but the execution of the weld has to be with the small root face so that there is no risk of fracture in the heat-affected zone.

The Houldcroft test was used for arriving at a comparison between the various types of aluminium alloys. These 'Edge-start cracking tests' were carried out in 6 mm thick test plates taken from 6 in. pipe with a wall thickness of 10 mm. The results were as follows:

Cracking Test No.	*Parent Material*	*Filler Material*	*Length of crack, mm In Radiograph*	*At × 10 magnification*
1	H9	None	37	37
2	H9	None	32	32
3	H9	None	38	38
4	H9	Al–5%Si	9	18
5	H9	Al–5%Si	8	23
6	H9	Al–5%Si	25	38

Welding took place both without filler metal and with welding wire of the Al–5% Si type. It was found that sometimes the length of the crack, measured at a small magnification, was larger than as indicated by the radiograph. Indeed the parent metal is very susceptible to cracking, whereas an addition of Al–5% Si filler metal shows an improvement, although this is very small.

The difficulty of keeping the dilution constant when filler metal is used must be mentioned. This is also shown by the rather large differences in the lengths of the cracks found in the three tests made, which may in fact be due to our brief experience with this type of cracking test.

Skill

In the early part of this century welding technique was still in the early stages of development. It is well known and understood that the skill required in the pioneering days of welding is no longer comparable with the skill now demanded of the welder.

The welder engaged in routine arc welding of mild steel, *e.g.*, in the shipbuilding and structural industries, is practising a job for which the technique has been stabilised. The average welder has to pay attention to the following four points:

(*a*) Is the connection of the welding machine correct?
(*b*) Is the current setting appropriate to the diameter of the electrode?
(*c*) Is the electrode dry?
(*d*) Is the welding position the most favourable?

When these points have been attended to, welding starts. After the electrode has been deposited, the slag will be removed from the weld, and in some places crater cracks may have to be removed.

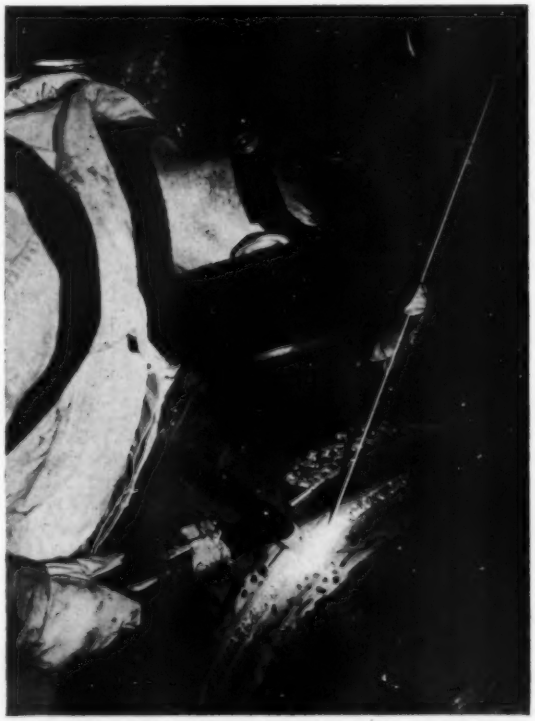
It can thus be shown that the check-list for the average welder is rather small and that he has only to pay attention to the four points mentioned, of which the greater part is still incorporated in the daily routine work.

It is possible that the pioneer welder in the early part of the century was something of an artist, but today all artistry has disappeared from ordinary labour. With further development of the technique further processes have also arisen. During World War II, for example, inert-gas-tungsten-arc welding was developed for which the apparatus and the technique ask for more attention from the welder than does ordinary arc welding.

In comparison with the four routine check points for arc welding, tungsten-arc welding needs twelve. There is also further specialisation in this process and more recently the inert-gas-metal-arc process has arisen. From a technical aspect this is a normal development in an expanding technique.

The basic technique is routine work, but branches are developed which require more specialisation and greater concentration on the part of the operator (Fig. 10).

It is our experience that aluminium welding of high quality requires great concentration and skill. For a recent installation constructed in aluminium pipe, for which the highest standards were set, the check list for the welder contained about 50 points as shown in Table III.



10—Tungsten-arc welding requires concentration and skill

Table III

Check list for pipe welding

1.	Workshop	Temperature
2.	„	Free of draught
3.	Sitework	Weather
4.	„	Temperature
5.	„	Wind
6.	Workplace	Is workplace fenced-in?
7.	„	Is scaffolding satisfactory for welding?
8.	„	Are surroundings restful?
9.	„	„ „ clean?
10.	„	Who besides the welder and his helper are within fenced-in area?
11.	„	Are all welds accessible to the welder?
12.	„	Has the management on site been informed that welding is about to take place?
13.	Apparatus	Is transformer continuously connected?
14.	„	What type of transformer is used?
15.	„	Are hoses and cables in good condition?
16.	„	Is electrode correctly ground?
17.	„	Was end of filler rod cut off?
18.	„	Diameter of electrode
19.	„	Projection of electrode beyond nozzle
20.	„	What nozzle size has to be used?
21.	„	Is nozzle entirely clean on both inside and outside?
22.	„	Make of welding wire, type, diameter
23.	„	Was wire stored in a dry place?
24.	„	How was wire cleaned?
25.	Dimensions of welding groove	Welding groove prepared by...
26.	„	Bottom width of groove
27.	„	Top width of groove
28.	„	Root face thickness
29.	„	Are root faces fitting exactly against each other?
30.	„	Surface condition of welding groove
31.	„	Scraping of groove surfaces
32.	„	Are sharp edges removed and smoothly finished?
33.	Planning of the welding	Is pipe to be welded sufficiently supported?
34.		Is pipe closed at top?
35.	„	Is pipe open at bottom?
36.	„	Is pipe internally heated from bottom?
37.	„	Has electrical preheating taken place?
38.	„	Is adjacent pipe covered by means of asbestos blankets?
39.	„	Are temperatures electrically measured?
40.	„	Are all tack welds sufficiently chipped out?
41.	„	Are craters chipped out correctly?
42.	„	Welding current
43.	„	Gas flow
44.	„	Is arc sputtering?
45.	Remarks	Wooden plugs are not allowable
46.	„	Brushing should only be used lightly especially on hot tube
47.	„	Filing not allowable, unless followed by firm scraping

It is clear that this task is too complicated for the average welder. A number of these points can be centrally complied with in shop welding, but on site this is more difficult because the welders are working more on their own.

In practice this means that each welder has a helper with him, so that the welder will be able to concentrate on his arc. This helper gives not only manual aid but generally he should also have sufficient knowledge to be able to realise the importance of the points on the check list.

From the foregoing it is clear that the level of skill required by both these people is rather high. Moreover —and this is based on our own experience—the welder should be very energetic and must not be too disappointed in case of bad luck; he should have an 'angel's patience'!

Safety Precautions

Owing to the intensive ultra-violet radiation from the arc, extra dark glasses are used in the helmet; it is recommended that well-closed clothes should be worn and that ultra-violet absorptive paint should be used on the surrounding walls.

Protective gloves, although they are not very practical for the welder, are necessary so as to prevent burning of the skin.

Working with de-greasing liquids such as tri- and tetra-chlorethylene is to be avoided owing to the development of phosgene gas near the welding arc.

Nevertheless, for welding aluminium, the foregoing precautions generally involve no hindrance to the welder.

It is evident that the work must be carried out in well ventilated rooms. For safety's sake it is recommended that adjacent personnel make use of safety spectacles, so that the risk of 'arc-eye' is limited. Ordinary glass already gives a certain protection to the eyes against ultra-violet radiation.

Non-Destructive Examination of Aluminium and Its Alloys

Radiography

Based on experience gained during X-ray inspection in aircraft construction, the periodical examination of aircraft parts, and that made during the examination of welds for the Nuclear Reactor at Petten, it is possible to give an impression of the problems connected with the radiography of aluminium.

For good interpretation of the radiograph, it is necessary that the highest quality X-ray technique be employed; this is particularly important in view of the very fine indications which may be seen in radiographs of aluminium welds.

It is known that high image quality is claimed for radiographs of steel, and there are many factors which may influence the quality of the radiograph. For aluminium, these factors are of greater importance. Based on the following survey, only some of them will be explained, since it is not possible to deal with all factors relating to the image quality. However, the quality of a radiograph depends largely upon the sharpness of the radiographic contrasts (see Fig. 14).

(1) *Inherent unsharpness as a result of scattered radiation in the film emulsion*

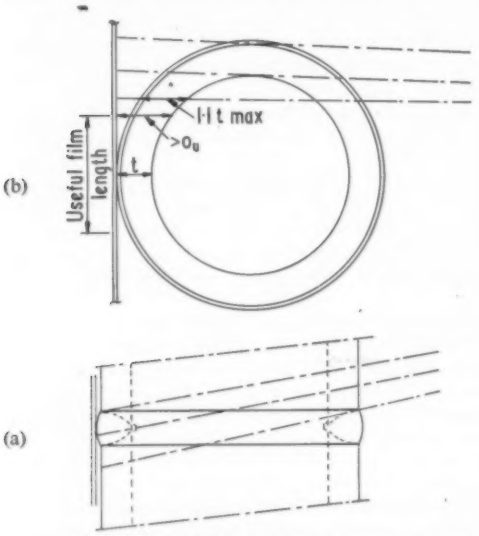
This unsharpness increases in proportion to the energy of the X-ray source. The absorption capacity of aluminium being considerably lower than that of steel, it may be possible to use a lower kilovoltage than with similar thicknesses of steel.

The scattered radiation in the emulsion will therefore become smaller, so that the unsharpness will be reduced.

(2) *Unsharpness as a result of grain size, thickness of the emulsion layer, and double emulsion layer*

This depends on the type of film (high speed or fine grain). It is important to choose the correct type of film, as governed by practical considerations.

In view of the nature of the defects which may occur in aluminium welds a fine-grain film is preferable. The double emulsion layer is—especially for the examination of pipe welding—disturbing because of the so-called 'image shift'. This image shifting necessitates



11*a–b*—*Films in flat position in contact with weld*

that, for pipe welding, more exposures have to be made (Figs. 11*a* and *b*).

(3) *Unsharpness due to the development process*

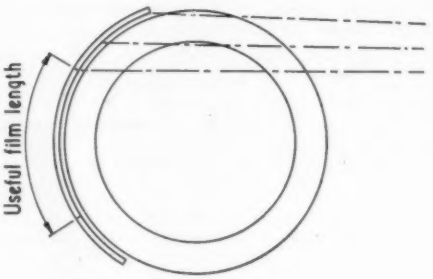
To avoid this unsharpness as far as possible, a developer must be used which is specially adapted to the fine-grain film.

(4) *Unsharpness due to the use of intensifying screens*

For the examination of steel in the Netherlands, salt screens are rarely used, and for aluminium neither salt nor lead screens are applied. This is due to the small absorption capacity of aluminium and the small kilovoltage which is required. The application of lead screens is useful only when the required voltage exceeds 120 kV. At below approx. 120 kV the lead screen will not have an intensifying effect, but it will result in poorer contrast; thus a higher kilovoltage than is strictly necessary would therefore be required.

(5) *Outside unsharpness*

As far as the outside unsharpness is concerned, the important factors do not differ from those which influence the examination of steel. The small absorption capacity of aluminium alloys means that the focal spot of the X-ray tube can be smaller, because of the lower kilovoltage needed. By using an apparatus adapted to this smaller voltage it is possible to make



11*c*—*Film around weld*

the film–focus distance smaller. This is of particular importance for the examination of pipewelds (Fig. 11*c*).

(6) *Contrast*

The contrast depends to a large extent on the X-ray technique.

(7) *Type of film*

The choice of the film in relation to the grain size and the unsharpness for the examination of aluminium has already been mentioned. Contrast depends on the fineness of the grain; with a coarse grain size the contrast is less than with a fine-grain film exposed at the same kilovoltage. The choice of the film thus depends not only on the sharpness but also on the contrast; for optimum results it will be necessary to select a fine-grain film.

(8) *Type of apparatus*

The difference between a d.c. and an a.c. apparatus is very small, so that a.c. apparatus is preferred because of its easy manipulation.

(9) *Filters*

The best contrast will be obtained when the lowest kilovoltage is used. It is therefore important to make as much use as possible of the so-called 'soft' rays by preventing their absorption by the frame of the X-ray tube. To achieve this, it is recommended that use be made of X-ray equipment in which the frame is made from beryllium, which has a very small absorption capacity.

(10) *Kilovoltage*

It is evident that the kilovoltage is related to the thickness of the material to be X-rayed, but sometimes the shape of the object (large differences in thickness) makes it necessary to use a higher kilovoltage so as to attain a greater contrast. Moreover, the product 'milliampere-minute' must also be related to the thickness.

(11) *Exposure technique* (see Appendix)

It has been stated that the examination of welds in aluminium is, in principal, similar to that of welds in steel. Only for the examination of pipe welds is there a difference, because not only is the complete weld examined but, in the first place, the root pass is checked. When this is proved to be satisfactory the weld is completed and finally radiographed.

(12) *Fog*

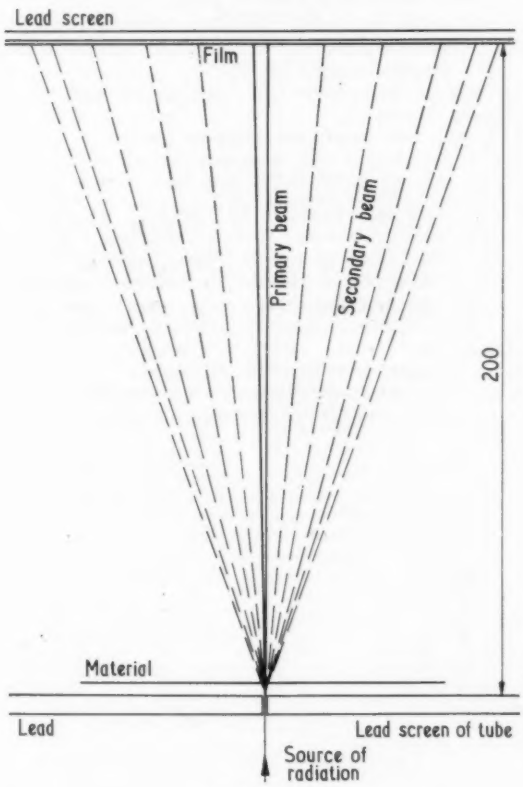
It is necessary to protect the film by means of lead on the side opposite to the X-ray source, so as to avoid fogging the film by reflected rays.

With aluminium the use of soft rays produces an effect which will manifest itself as lines on the film. This is the so-called 'Laue-effect'. The extent to which these lines appear depends largely on the structure of the material (Fig. 12).

(13) *Darkroom technique*

It would take too much space to deal with this subject in detail so only a few short remarks will be made.

Type of developer: To be related to the film.
Use of glacial acetic acid: This is used to neutralise the developer, so that fog will be avoided and the film will be bright (contrast improvement).
Age of developer: Hydrochinon and Metol, being additives to the developer, have a different affinity with oxygen, so that in time the composition will become unbalanced and the quality of the radiographs will suffer.
Developing time: Too short or too long a developing time results in poor contrast and an enlarging of the grain size of the film.
Age of films: Films which have been kept in stock for a long time show a tendency to fog, which will diminish the brightness of the image.
Film defects caused by handling: The handling of the film is very important, since carelessness may damage the very fine image and hamper the interpretation.
Film production defects: It is necessary that attention be paid to this point, since production defects may interfere with the interpretation of the radiograph.



12—*Laue effect*

All these points, so far as the darkroom technique is concerned are, in line with current practice.

(14) *Interpretation*

A good technique shows both the defects in and the structure of the weld. The difficulty is therefore to distinguish between very fine defects and the structure. It is necessary to have experience for the correct interpretation of aluminium radiographs.

(15) *Defects that can occur in welds*

A=gaspores
Aa=porosity
Ab=worm holes

B=slag
Ba=slag of any shape and direction
Bb=slag line

C=lack of fusion

D=incomplete root penetration

E=cracks
Ea=longitudinal cracks
Eb=transverse cracks
Ec=crater cracks

F=undercut

G=slag inclusions
H=tungsten inclusions

I=oxide inclusions

Ultrasonic examination

It is understood that the ultrasonic examination of aluminium welds does not differ from the technique applied to the examination of welds in steel.

Examination of welds in relatively thin plates (12 mm and less) is, as in the case of steel, more difficult than the examination of thicker material.

In the main, the difficulty is the exact determination of the location of defects, which is required for a good analysis of the observed discontinuities.

In thin plate, the bead is relatively thick and can reflect the waves, so making the examination more difficult.

(1) *The structure*

No difficulties have been reported in the ultrasonic examination of welds in aluminium arising from the material structure, such as are experienced in the examination of welds in stainless steel. In general it appears that the method, in this respect, also as it concerns the accoustic coupling between probes and material, is more favourable.

(2) *Refraction*

A point which has to be considered is that, owing to the difference in velocity of ultrasonic waves in steel and aluminium, angle probes have to be corrected when they are set for steel. Not only is there a difference in the angle of refraction, but the probe index is also changed.

(3) *Reference block*

It is necessary to calibrate and check the apparatus and probes on an aluminium reference block.

(4) *Analysis of defects*

An exact analysis of defects is not yet possible. It is even doubtful whether some of the discontinuities which may occur in aluminium welds can in fact be identified by a normal technique; for example, oxide inclusions and incomplete root penetration where the root faces are completely in contact.

It is therefore an open question whether at present ultrasonic inspection is satisfactory for finding these defects economically.

Penetrant testing

For the surfaces of welds in aluminium the method pre-eminently suitable is the penetrant test.

As an example, for tack welds in which the occurrence of crater cracks is feared, this method is most effective. The penetrant liquids used may be of the dye or fluorescent types. Nowadays various very useful variations of these types are on the market; and it is largely a question of taste in a figurative sense, and perhaps of smell in a literal sense, which decides the type to be chosen. There is yet no good method of checking and comparing the various penetrants available; indeed, various suggestions have been made and this subject is also under investigations by Commission V (E) of the IIW.

Technique

The technique of penetrant testing involves:

(*a*) Thorough cleaning
(*b*) Sufficient time
(*c*) Careful elimination of superfluous penetrant
(*d*) Still more careful addition of the developer.

It is usual practice for each manufacturer to supply his own instructions for use with his liquids, and in these instructions important variations occur.

It may still be of use to point out the importance of a good developer. It is the general opinion that the penetrant liquid itself is the most important factor, but in our view a good developer is at least, and perhaps still more, important.

APPENDIX

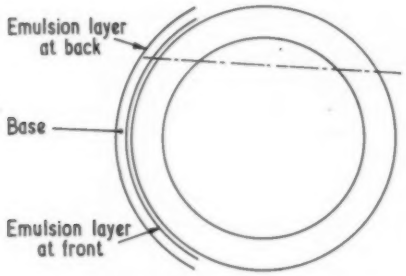
Radiographic Exposure Techniques

Method I

Focus–film distance 80 cm: Films in flat position in contact with weld.

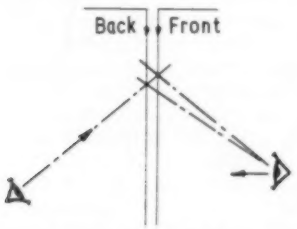
Exposure technique incorrect because:

1. Arrangement of apparatus gives difficulties:
   (*a*) large focus–film distance cannot always be complied with
   (*b*) incident angle difficult (see Fig. 13*a*).



13*a*—*Film around weld*

2. Incident angle (Fig. 13*a*) gives a risk that root of weld may be missed.
3. Usable film length short, owing to:
   (*a*) increase of wall thickness (large) (see Fig. 13*b*)
   (*b*) density variation (large) (see Fig. 13*b*)
   (*c*) figuration defect on film (large) (see Fig. 13*b*)
   (d) unsharpness increases towards sides of film.



13*b*—*Position of film during examination*

4. Long exposure time in connection with focus–film distance.
5. Large number of exposures is necessary owing to the short usable film length.

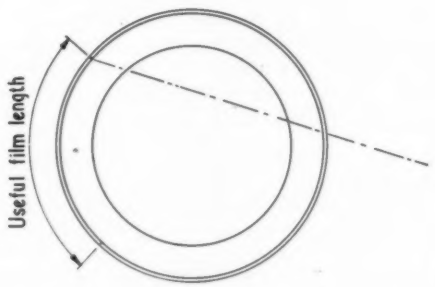
Method II

Focus–film distance 80 cm: Film around the weld

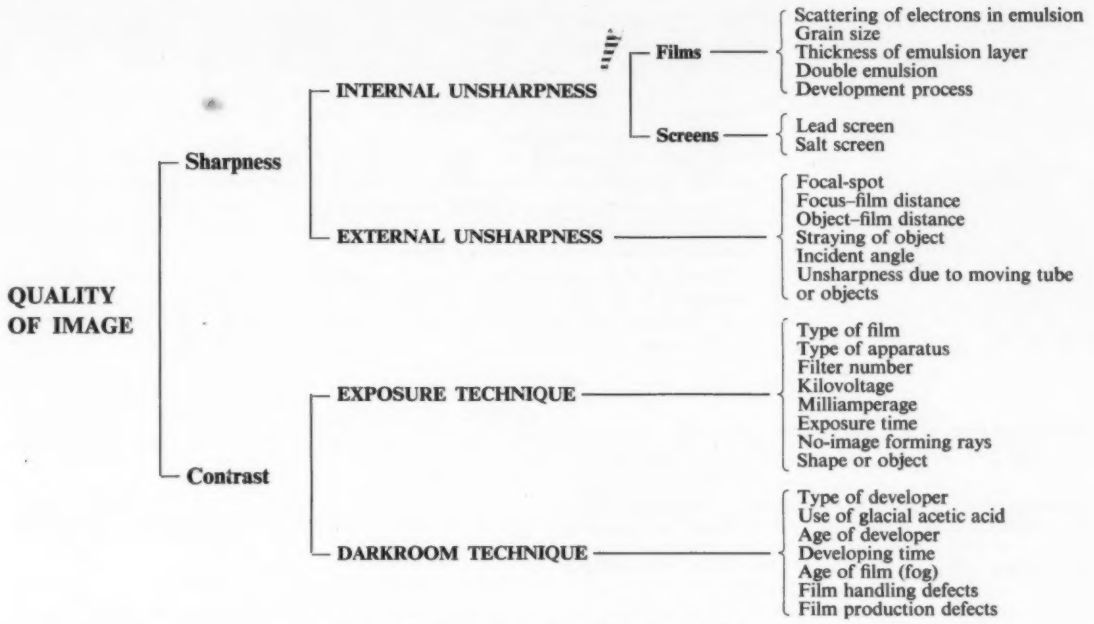
Exposure technique incorrect, because:

1. Arrangement of apparatus gives difficulties:
   (*a*) large focus–film distance cannot always be complied with
   (*b*) incident angle difficult.
2. Incident angle gives the risk that the root of the weld is missed.
3. Usable film length short, owing to:
   (*a*) increase of wall thickness (large)
   (*b*) density variation (large)
   (*c*) figuration defect on film (large)
   (*d*) unsharpness increases, somewhat less than with Method I, but image shifting effect is found owing to double emulsion layer (see Figs. 11*a* and *b*)
4. Long exposure time in relation to focus–film distance.
5. Large number of exposure in necessary.

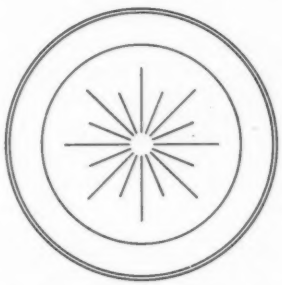
Note: for the interpretation of the films the double emulsion layer has to be taken into account.



13*c*—*Focus–film distance as short as possible*



14—*Factors which influence the exposure quality of radiographs*



13*d*—*Central X-ray source, with film all round weld*

Method III

Focus–film distance as short as possible

All disadvantages mentioned for Methods I and II are diminished.

The only disadvantage is that the outer unsharpness is increased considerably. However, this objection can be remedied by application of an X-ray tube having a very small focal-spot (Fig. 13*c*).

Method IV

Central arrangement of X-ray source: Film around the entire weld

This is the most ideal arrangement, but the focal-spot must be very small (Fig. 13*d*).

A NEW POST-GRADUATE COURSE IN WELDING TECHNOLOGY

It is with much pleasure that the Institute is able to announce the organisation of a Post-Graduate Course in Welding Technology, which the Ministry of Education has set up in response to the representations of the Institute of Welding and the British Welding Research Association, at the College of Aeronautics, Cranfield; this Course will open in the Autumn of this year. The prospectus is printed below.

Already the minimum enrolment to ensure the holding of the Course has been secured as a result of promises from A.E.I. (Manchester) Limited, British Oxygen Company Limited and Whessoe Limited. The British Oxygen Company has also promised to endow two Bursaries for a period of seven years, the candidates to be selected by the Institute.

In the U.S.A. and in the U.S.S.R. provision for the education of Welding specialists is of long standing, so that the supply of qualified men far exceeds what is available in this country. This new course is, therefore, a most important development.

Prospectus

Purpose and Content of the Course

The purpose of the course, which has been sponsored by the Institute of Welding and the British Welding Research Association, is to provide students of graduate status in either metallurgy or engineering with a specialised training to fit them for posts in the design, development and production departments of the many industries where welding is now vital. To do this, a range of subjects will be covered with a particular concentration on (*a*) the special metallurgical consideration inherent in welding; (*b*) the welding processes, their characteristics and fields of application, and (*c*) design for welding and the essential production techniques. The course is thus a compound of mechanical and civil engineering and metallurgy, and has been organised with the object of producing a specialist in welding science and technology, capable of appreciating and dealing with the special problems which welding raises, and competent to advise on and direct the course of developments in the field.

Although the main content of the course is common for all types of student, special provision is made at the beginning of the course to strengthen the metallurgist's knowledge of engineering and the engineer's knowledge of metallurgy. In a few cases, it may be possible for individual students to give some special attention to specific topics which may be of particular interest to them and to their organisations, but this will be exceptional rather than usual.

The course is designed to be comprehensive, and an idea of its scope may be gained from the following summary.

The metallurgical teaching will include lectures on applied metallurgy generally, particularly in relation to steels, as well as those special questions raised by the welding process; solidification, the heat-affected zone, the fundamental character of the weld metal, and so on. The mechanical properties of welds and welded assemblies will be extensively treated, including brittle fracture, creep, fatigue, residual stresses and crack-initiation and propagation. Methods of inspection and testing by both non-destructive techniques and by mechanical test, and the technology of all the welding processes will be covered by the teaching and will be directly demonstrated. The design teaching will include basic instruction in stress analysis and in the principles of elastic and plastic design, and will extend this theory to the specific case of welded structures, and to an examination of welded joints and connections. The most important consideration in design is to develop in designers a feeling for the special factors which arise in welded assemblies, so that the whole project before them can be seen in these terms. The special electrical considerations which arise in welding, as well as the production aspects, industrial organisation and automatic control will also be thoroughly examined.

A vacation course in practical arc and gas welding is included in the programme to introduce students to the essential "feel" of the subject.

Award of Diploma

Students who attain a satisfactory standard in the course will be awarded the Diploma in Advanced Engineering (D.A.E.)

Standard of Entry

All candidates will, in the first place, be interviewed by the Head of the Department of Materials or his nominee.

The level of instruction will be post-graduate and the candidates will normally be expected to hold honours degrees of approved universities in appropriate subjects. The College Board of Entry may require candidates to take either an oral or a written examination.

Duration of the Course

The course will take place during the Autumn, Spring and Summer terms of the academic year 1961–1962. The dates for the terms are:

Autumn Term	9th October to 15th December, 1961.
Spring Term	15th January to 30th March, 1962.
Summer Term	30th April to 6th July, 1962.

Cost

The charge for tuition and residence for the complete year are as follows:

Tuition—
British Students, £75.
Commonwealth Students, £250.
Foreign Students, £350.
Residence—£126 10s. 0d.

The residence charge includes the cost of full board during the terms and the rent of an individual study-bedroom.

Bursaries

Students of British nationality domiciled in the United Kingdom who are accepted for entry to the course are eligible, if not already supported by a sponsoring firm or institution, to make application for a grant from the College Bursary Fund.

An individual concern will support two Bursaries to encourage engineers and metallurgists to enter the welding field.

Applications

Forms of application for the course may be obtained from:

THE WARDEN,
THE COLLEGE OF AERONAUTICS,
CRANFIELD, BLETCHLEY, BUCKS.

Welding RESEARCH

B.W.R.A. REPORT

By A. A. Wells, B.SC. (ENG.), PH.D.

Brittle Fracture Strength of Welded Steel Plates

TESTS ON FIVE FURTHER STEELS

Synopsis

The results of tensile tests on sixty steel plates, each 3 ft wide and 1 in. thick, are described. A mild steel, a semi-killed higher manganese low-carbon steel, and three fully-killed normalised steels were tested. The samples were artificially notched in edges prepared for butt welding, which was carried out along the plate centres in the direction of tension. At the temperatures chosen for test, many brittle fractures were obtained at externally applied loads well below yield-point value, and in twelve of these cases fractures passed through the plates without arrest. In all cases where fracture occurred at such low loads that crack arrest followed, loads sufficient to cause general yield of the remaining cross-sections were necessary for re-initiation. Thus, if shifts of transition temperature from one steel to another are taken into account, the results in general compare well with those described in a previous paper.

Extensive correlation with small-scale transition-temperature tests on the same steels has been achieved in collaboration with the Admiralty Advisory Committee on Structural Steel. This confirms that more reliance may be placed on fracture appearance in small-scale tests than on impact energy in the Charpy test, although both criteria leave something to be desired. It is noted that no low-load through fractures occurred at temperatures above Robertson crack arrest temperatures, and that the highest temperatures at which short brittle cracks could be produced in the wide plates, after fully plastic strain, were uniformly about 15–20°C. above the Robertson crack arrest and the Pellini drop weight transition temperatures. It is concluded that the absence of extensive prefracture plastic deformation in the latter tests represents a desirable property in a small-scale test.

Sufficient mild steel specimens were tested to establish that welds deposited with low-hydrogen basic electrodes afford significantly higher fracture strength than those produced with rutile-covered electrodes. This is linked to a difference in the post-weld cracking tendencies of the weld deposits in the two cases.

Prefracture plastic extensions of the plates at the highest temperatures for observing any vestige of brittle behaviour (i.e., *temperatures mainly above the small-scale test fracture appearance transition temperatures*) *were of the order of 1%. This is of the same order as in notched, welded, and furnace stress relieved mild steel plate, tested at the temperature at which low-load brittle fractures occur in as-welded plates of the fully-killed and normalised steels.*

Foreword

The work described in the following papers is an extension of the investigation into the brittle fracture strength of welded steel plates first reported by Dr. A. A. Wells in the *Transactions of the Institute of Naval Architects*, 1956, vol. 98. An examination of the five steels used in the tests and of the fracture origins was made by Mr. P. Whitaker of the Research Department, Stewarts & Lloyds Ltd., Corby, whose observations are given in the second appendix.

A further study, of the effects on the five steels of plastic strain, ageing, and stress relieving, has been made by Dr. C. F. Tipper, Engineering Department, Cambridge University, and the results of this work are published in the last paper of the group.

Introduction

In a previous paper[1] large-scale tensile tests were described in which brittle fractures in steel plates were produced at low applied stresses when:

(i) The plate contained a central butt weld in the direction of tension
(ii) A notch was present close to the butt weld (the notch consisted of sawcuts in the edges of the plate prepared for welding, as suggested by Greene[2])
(iii) The test was carried out at a temperature below the transition temperature of the parent material (determined by energy absorption or fracture appearance in a small-scale test, such as the Charpy V).

Results were presented for one semi-killed low-carbon steel, and a tentative explanation of the fracture mechanism was appended.

It is well known that a steel plate, when sharply notched and tested in tension at a temperature not more than, say, 100°C. below the fracture appearance transition, will fail through a brittle fracture only after some degree of fully plastic extension. This behaviour is not changed for any plate width up to the largest values which it has been possible to test. In simply notched laboratory test pieces, at such temperatures, fracture before the onset of general yield appears to have been recorded only in the case of massive alloy steel specimens, such as the turbine rotor forgings tested by Winne and Wundt.[3] In the wide plate tests just mentioned fracture initiations at loads lower than general yield were therefore ascribed to the combined effects of the notch and the welded joint, and particularly to strain hardening and strain ageing resulting from concentrated plastic flow at the notch roots. The latter would be expected to occur during weld cooling, when restraint of natural shrinkage along the direction of the weld would arise from rigidity of the adjacent large cross-sections of unheated material.

A significant feature of brittle crack propagation in the wide plate specimens was the distinction between arrested and through fractures, depending upon the applied stress at which initiation took place. Thus, crack arrest occurred only with spontaneous initiation (cooling without external load), or with external loads giving rise to average stresses less than about one third of the yield point. The crack lengths at arrest appeared to be greater than the extent of the tensile residual stress zone from the butt welded joint. Qualitatively, it appeared that the application of definite minimum stresses (averaged over the cross-section) was required, before fracture commenced, in order to maintain propagation.

A quantitative study of conditions for crack propagation was made in terms of the concept of crack extension force and fracture toughness.* The concept has been extensively described[4] and was adopted owing to its relevance to conditions near the crack root during propagation. It is noteworthy, however, that where elastic materials are concerned the treatment may equally well be described in terms of stress and stress gradient, as pointed out by Irwin[4] and Neuber.[5] In the butt welded plate, under conditions of combined tensile residual and externally applied stresses, with a crack spreading transversely and symmetrically from the weld, it was shown that the crack extension force reaches a maximum when the length of the extending crack is close to the width of the heat-affected zone. It falls to a minimum for a length corresponding with that usually observed when arrest takes place, and then rises again. An improved method of computing the crack extension force for an arbitrary distribution of welding residual stress has recently been devised and applied by Masubuchi,[6] and additional wide plate tests of similar type to those already described and yielding similar results have been performed by Kihara and Masubuchi.[7]

Although the low-stress fracture behaviour may be regarded as at least partly understood, a need existed to extend the work to a wider variety of steels, and to correlate the behaviour of such steels in the wide plate test with the results of some of the current smaller scale tests for the assessment of transition temperature in steels. This need is met in part by the Japanese work, which has been published since the decision was made to investigate the behaviour of semi-killed steels with higher manganese contents, and fully-killed and normalised steels. Adequately large quantities of 1 in. thick plate of three such steels (*P*, *Q* and *S*) were made available by the Heavy Steel Makers Association. While the work was in progress, a programme of large- and small-scale tests to correlate transition temperatures was begun by the Admiralty Advisory Committee on Structural Steel and, at their request, a proportion of each of steels *P*, *Q* and *S* was allocated for the programme. Quantities of fully-killed and normalised steels *R* and *T* were received in exchange. The tests now to be described are thus concerned with five steels with different characteristics. The chemical compositions, mechanical properties, and small-scale transition temperature test data reported are those arising from the Admiralty programme because of its greater concentration on this aspect. Further information on the steels is available in the Admiralty report.[8]

As knowledge is accumulated on the various brittle fracture transition properties, it may be possible to devise simpler and more direct testing methods. For this reason the remainder of these now extensively pedigreed steels are to be preserved indefinitely.

Materials

The designations of the five steels, all made by the basic open-hearth process, are as follows:

P	Semi-killed mild steel
Q	Semi-killed mild steel with a higher manganese/carbon ratio
R, *S* and *T*	Fully-killed grain-controlled normalised mild steels

Chemical compositions and mechanical properties are given in Table I and typical micro-structures in

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Report B6/1/58 of the British Welding Research Association, circulated to members in November 1959.
Dr. Wells is Assistant Director of Research of the Association.
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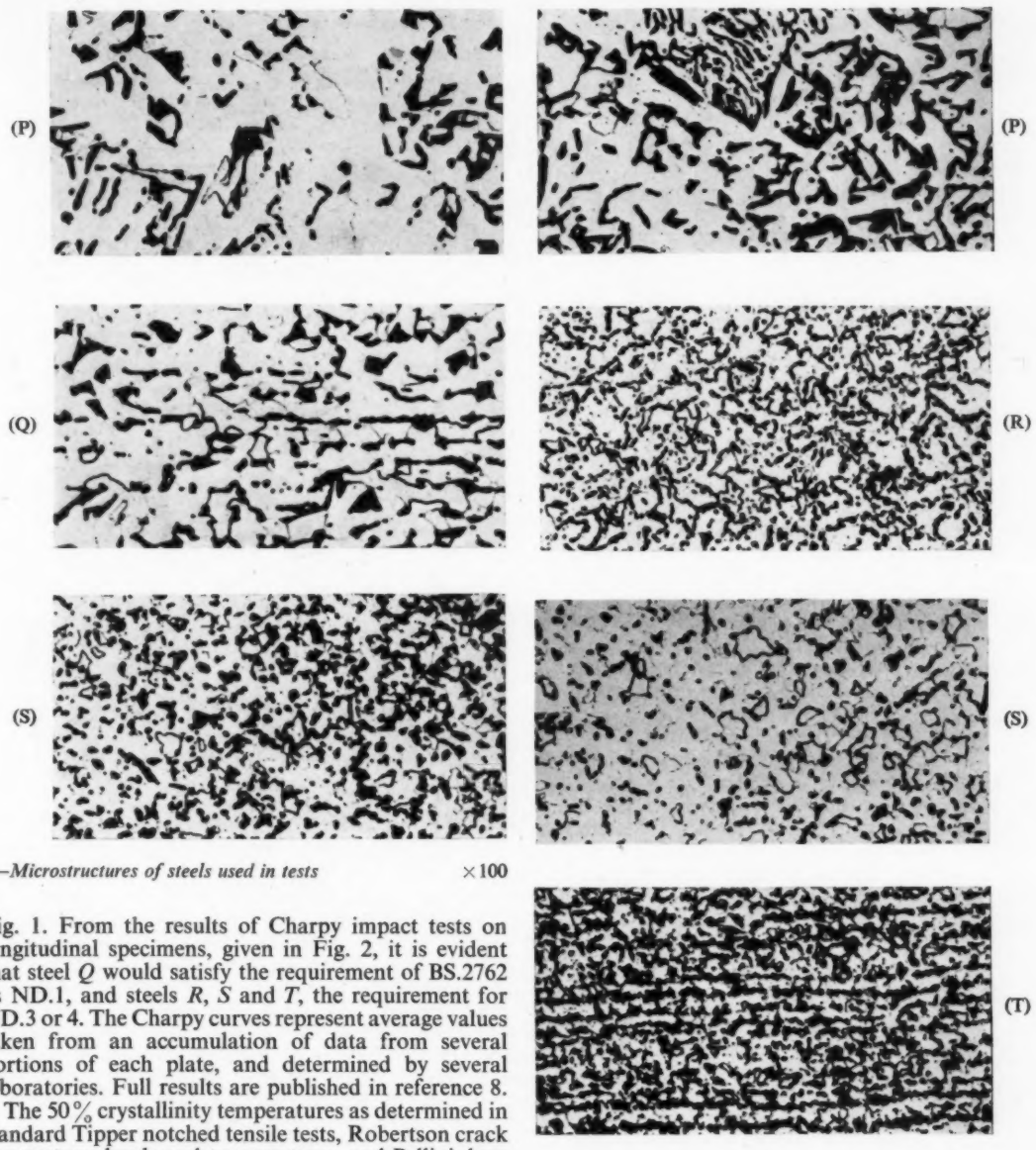
* In recognition of a terminology revision, the terms "crack extension force" and "fracture toughness" replace those used for the same quantities in the earlier report, *i.e.*, "strain energy release rate" and "surface energy" respectively. It should be noted that the units: energy (work) per unit area, and force per unit thickness, are also synonymous.



1—*Microstructures of steels used in tests* ×100

Fig. 1. From the results of Charpy impact tests on longitudinal specimens, given in Fig. 2, it is evident that steel *Q* would satisfy the requirement of BS.2762 as ND.1, and steels *R*, *S* and *T*, the requirement for ND.3 or 4. The Charpy curves represent average values taken from an accumulation of data from several portions of each plate, and determined by several laboratories. Full results are published in reference 8.

The 50% crystallinity temperatures as determined in standard Tipper notched tensile tests, Robertson crack arrest stress levels and temperatures, and Pellini drop weight nil ductility temperatures are also shown in Fig. 2.

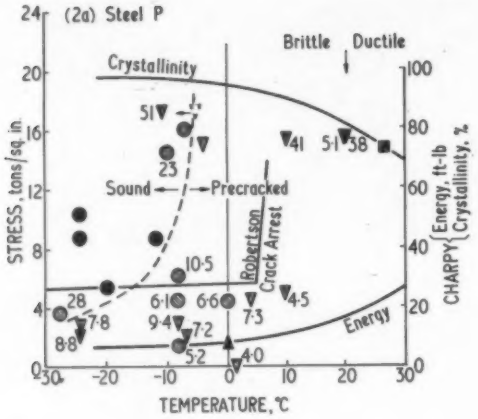
Specimen Preparation

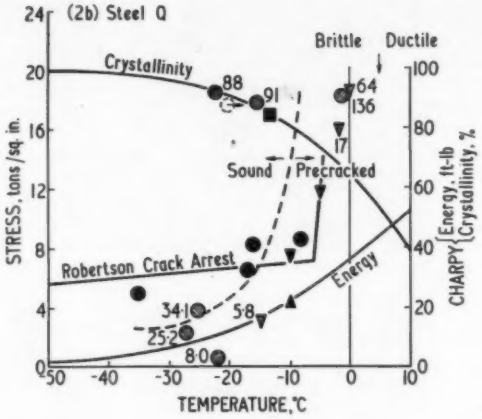
Test plates were prepared to sustain tension parallel to the direction of rolling exactly as described for previous tests. The method of making jeweller's saw cuts in the edges prepared for longitudinal butt welding was also as before. At the beginning of the programme multi-run manual welds were deposited using E.319 (BS.1719) rutile-covered electrodes. After a number of specimens had been prepared some difficulty was experienced with longitudinal cracking. A change was therefore made in that root runs in subsequent butt welds were deposited with E.615 low-hydrogen basic-covered electrodes. Longitudinal cracking was eliminated in this way, but some differences were then observed in the behaviour of the specimens so made; these are described later in the report. The effect was thought to be worth investigating and results for each steel (except *R*) were obtained with specimens representing both welding methods.

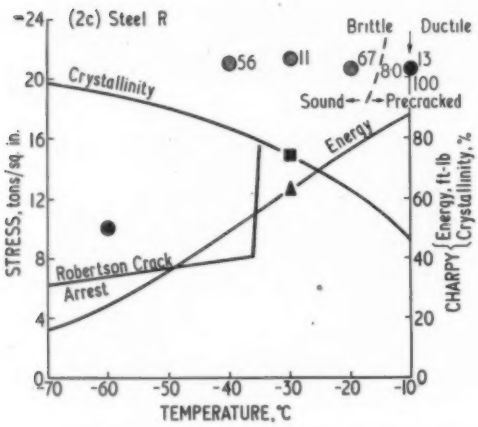
No further changes in specimen preparation were made from the method described in reference 1.

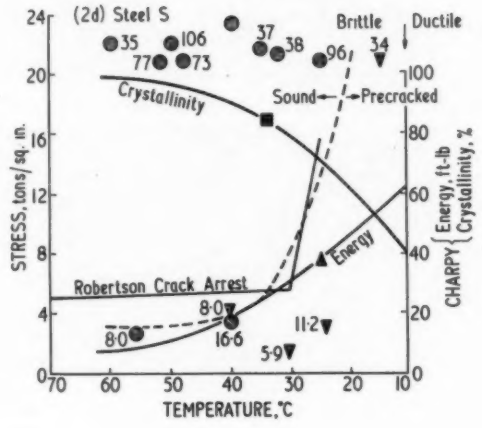
Loading

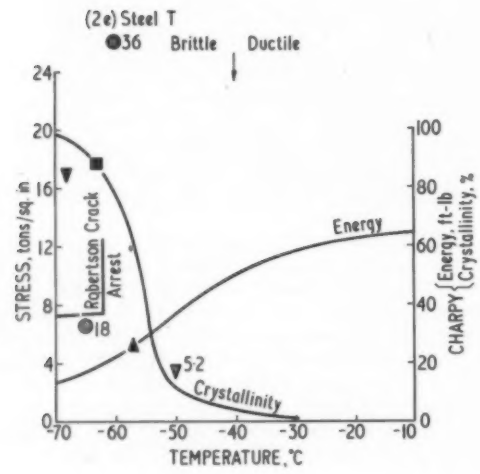
The method of loading, using a test rig of the type described in reference 9, was that shown in reference 1. However, for the specimens from steels *R*, *S* and *T*,

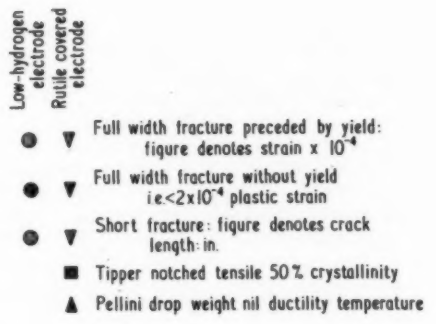











Low-hydrogen electrode
Rutile covered electrode
Full width fracture preceded by yield: figure denotes strain x 10⁻⁴
Full width fracture without yield i.e. <2x10⁻⁴ plastic strain
Short fracture: figure denotes crack length: in.
Tipper notched tensile 50% crystallinity
Pellini drop weight nil ductility temperature

2—Fracture strengths and Robertson transition data of wide plates in relation to temperature: (a) *Steel P;* (b): *steel Q;* (c) *steel R;* (d) *steel S;* (e) *steel T*

Table I

Chemical compositions and mechanical properties

		Steels P	Q	R	S	T
Composition, % wt						
C		0·18	0·14	0·12	0·15	0·15
Mn		0·54	1·07	1·43	1·05	1·43
Si		0·04	0·02	0·18	0·17	0·28
S		0·039	0·042	0·035	0·041	0·040
P		0·026	0·039	0·027	0·028	0·028
Ni		0·15	0·03	0·04	0·04	0·03
Sn		0·024	0·013	0·023	0·025	0·024
Cu		0·10	0·08	0·10	0·08	0·07
Cr		0·06	0·02	0·02	0·04	0·01
Al (Soluble)		0·005	0·001	0·071	0·005	0·083
N_2		0·005	0·006	0·004	0·006	0·004
H_2 ml/100 g		0·5	0·1	0·1	0·1	0·1
McQuaid-Ehn grain size		2	4–5	7	6	7
Ferrite grains per sq.in. $\times 10^6$		0·39	0·49	1·52	1·75	2·08
Fox inclusion count		87	95	102	78	104
Yield stress, tons/sq.in.	L	14·7	16·6	18·9	18·8	22·1
	T	14·9	16·3	17·6	19·4	22·0
0·3% proof stress, tons/sq.in.	L	17·5	16·8	18·9	18·9	22·1
	T	14·8	16·4	17·7	19·7	22·0
0·5% proof stress, tons/sq.in,	L	18·2	16·8	18·3	19·2	22·0
	T	14·9	16·3	17·6	19·6	21·6
U.T.S., tons/sq.in.	L	27·4	27·4	28·5	28·4	31·8
	T	26·5	27·2	28·5	28·7	31·9
Elong. on 8 in., %	L	24*	35	33	33	32
	T	31	35	33	33	28
Red. in area, %	L	54	62	71	67	62
	T	53	61	57	60	44

* Fractured near end of gauge length.
Chemical composition and inclusion counts are means of four values from differing zones.

tests were required at temperatures down to −60°C. and special provisions were necessary for this. In the first instance the yield points of the steels at these low temperatures were significantly greater than at room temperature and, to keep fracture potential within the load capacity of the equipment, the specimens were reduced in width to 30 in., after deposition of the central butt weld. The maintenance of similar conditions for restraint and heat flow during welding was observed by this waisting of the specimens, whilst the elastic distribution of applied stress during loading was not significantly modified by the change in width. With the high yield strength of steel *T*, even this width reduction was found inadequate. However, at this stage of the work, a test rig of 2,000 tons capacity became available, enabling tests to be made without the need for reduction in width.

To reach the lower temperatures, it was found necessary in all cases to supplement solid carbon dioxide cooling with insulation of all the free faces of the specimens. This was most conveniently achieved with the use of slabs of "Onozote" expanded rubber 1½ in. thick.

An attempt was also made to measure brittle fracture velocities, particularly in those specimens where through fractures were expected. For this purpose 51 s.w.g. hard drawn enamelled copper wires were cemented across each fracture path with a gauge length of 6 in. located midway between the butt weld and the plate edge. It was found that fine wires of this type were repeatedly severed by the passage of brittle cracks, although no information could be obtained as to the precise breaking point in relation to the tip of the advancing fracture. It was assumed that there would be identical time, and distance, lags for each wire. Each pair of wires was connected to an electronic interval timer, which indicated on decatron tubes the time lag between the breaking of the first and second wires.

Fractured Surfaces

After each test, fractured plate surfaces were cut out and preserved for future reference. Overheating was avoided by making the cuts at a distance of 3 in. on either side of the fracture. To prevent rusting of the fractured surfaces from low-temperature tests traces of frost and water were washed off with alcohol, followed immediately by an application of rust-inhibiting oil. For permanent preservation, the oil was later removed with acetone and a clear cellulose lacquer was applied.

In several instances attempts were made to study the condition of the material at the root of the saw cut after fracture, by microscopic observation of polished and etched transverse specimens. In spite of the knowledge that an embrittled condition existed at the root of the sawcuts, as shown by the low-stress fracture initiations, very little of interest was exposed when using the customary etching reagents with optical observation up to 2,000 diameters. However, in view of the importance of the conditions which permit low-stress initiation of brittle cracks in the specimens, further study is being made.

As a supplement to this information, hardness traverses across weld and heat-affected zone were made on at least one specimen for each steel. Charpy specimens were also machined from weld metal and heat-affected zones on broken wide plate specimens. These specimens had their long axes parallel to the weld and the notches were cut through the plate thickness.

Results

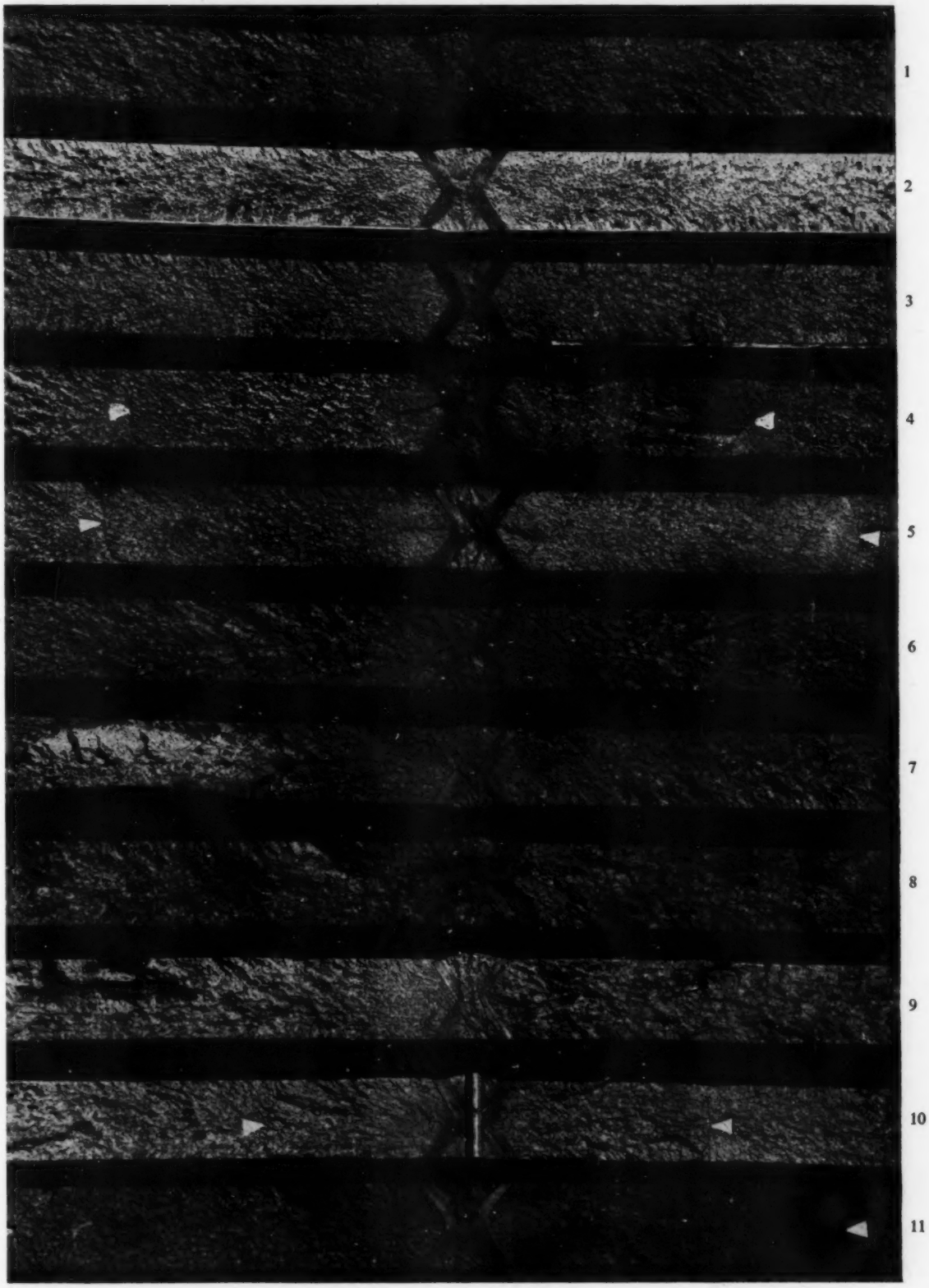
Information obtained from all the wide plate tests is summarised in Table II. The temperatures at fracture represent the mean values from three thermocouples, uniformly distributed over the test plates along the cracking plane. No cases exist where these temperatures varied over a range greater than ±½°C. The applied stresses were obtained by dividing load, immediately preceding either an arrested crack or a through fracture, by the gross cross-sectional area of each test plate. In all cases, after the occurrence of an arrested crack, the specimens were broken open. In no case did the applied stress (over the remaining cross-sectional area), for initiation of this second brittle fracture, differ by more than a few per cent from the yield point of the material at the relevant temperature. Applied stresses and extensions relevant to this fracture stage are also given in Table II. The lengths of arrested short cracks were measured from shear lip positions after complete fracture of the specimens. For consistency they are computed for the furthest extremities of the arrested crack, which generally coincided with the mid-thickness of the plate.

Table II

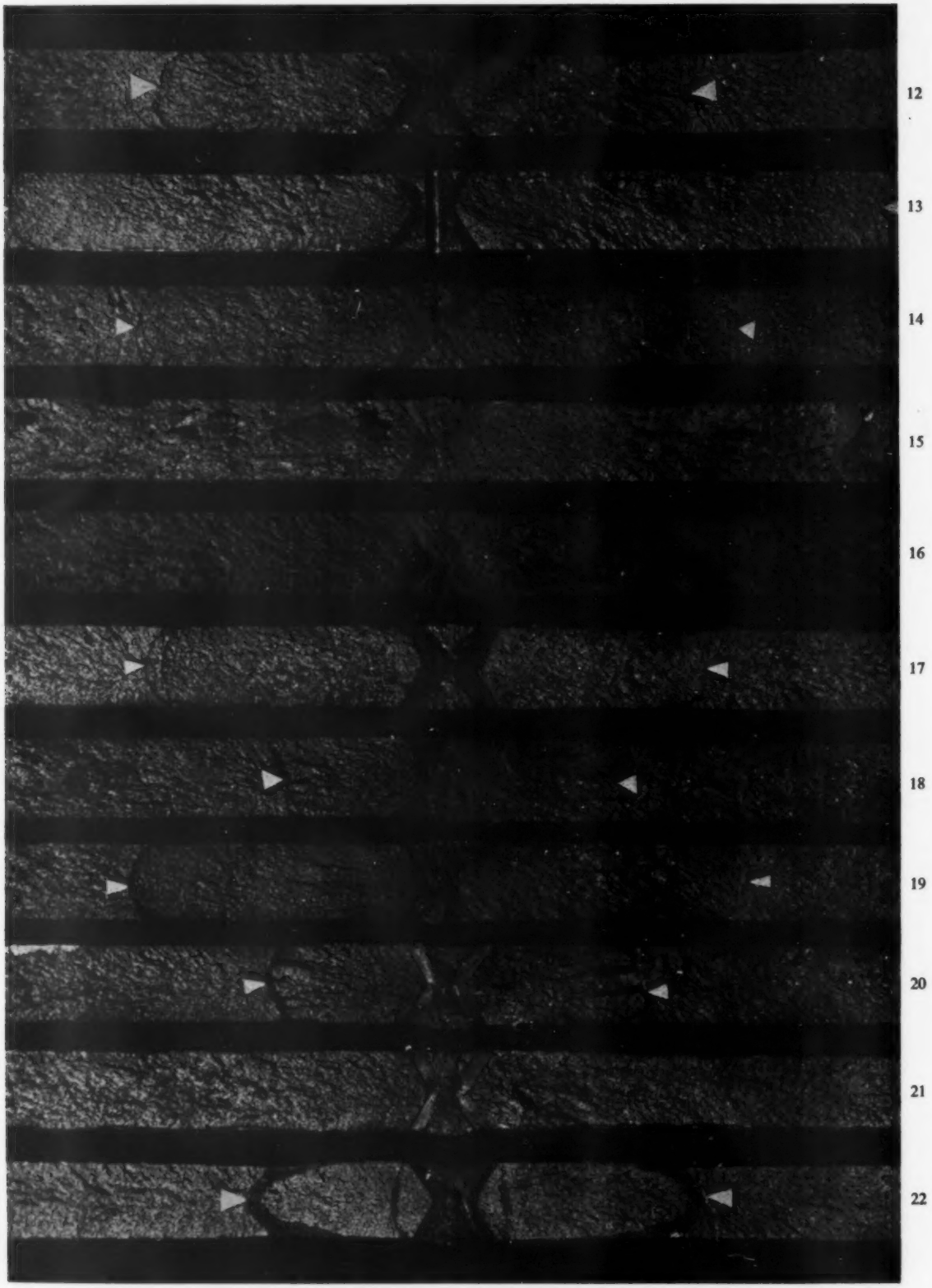
Wide plate fracture data

No.	Weld Detail	Test Temperature, °C.	Fracture Stress tons/sq.in.	Crack Length, in.	Prefracture extension $\times 10^{-4}$	Crack Velocity, ft/sec	Secondary Fracture Stress, tons/sq.in.	Secondary Fracture Ext. $\times 10^{-4}$
Steel P								
1	L	−28	3·5	28·0	—		18·4	0
2	L	−25	10·1	T	—	4170	—	—
3	L	−25	8·7	T	—	3330	—	—
4	RC	−25	2·3	7·8	—		16·3	2
5	RC	−25	1·9	8·8	—	3330	15·9	2
6	L	−20	5·2	T	—		—	—
7	L	−12	8·5	T	—		—	—
8	RC	− 5 (−11)	17·2	T	51		—	—
9	L	−10	14·4	T	23		—	—
10	LD	− 8	1·5	5·2	—		15·5	9
11	RC	− 8	2·7	9·4	—		15·1	
12	LC	− 8	4·4	6·1	—	6260	16·2	13
13	LD	− 8	6·0	10·5	—	3840	16·3	13
14	RC	− 7	1·8	7·2	—		15·0	6
15	L	− 7	16·0	T	?		—	—
16	RC	− 4	15·3	T	?		—	—
17	LC	0	4·2	6·6	—	2940	15·4	26
18	RC	1	0	4·0	—		15·5	10
19	RC	4	4·3	7·3	—	2940	15·9	5
20	RC	10	4·7	4·5	—		18·3	29
21	RC	10	15·2	T	41	4650	—	—
22	RC	20	15·4	5·1	38		18·0	84
Steel Q								
1	L	−35	5·0	T	—		—	—
2	LC	−27	2·3	25·2	—		20·2	112
3	L	−25	3·8	34·1	—		19·0	1
4	L	−22	0·8	8·0	—	1086	18·3	10
5	L	−11 (−22)	18·5	T	88		—	—
6	L	−20 (−15)	17·5	T	91		—	—
7	L	−17	6·6	T	—		—	—
8	L	−16	8·4	T	—		—	—
9	RC	−15	3·1	5·8	—	2000	19·6	31
10	RC	−10	7·4	T	—	2270	—	—
11	LC	− 8	8·6	T	—		—	—
12	RC	− 5	11·6	T	—		—	—
13	RC	− 2	15·8	T	17		—	—
14	LC	− 1	18·1	T	136		—	—
15	RC	0	18·1	T	64		—	—
Steel R								
1	L	−60	9·9	T	—		—	—
2	L	−40	21·0	T	56		—	—
3	L	−30	21·2	T	11		—	—
4	L	−20	20·5	T	67		—	—
5	LC	−10	20·5	8·0	13		24·5	179
Steel S								
1	L	−60	22·3	T	35		—	—
2	LC	−56	2·5	8·0	—		23·9	72
3	L	−52	21·0	T	77		—	—
4	L	−50	22·3	T	106		—	—
5	L	−48	21·0	T	73		—	—
6	L	−40	3·4	16·6	—		23·9	50
7	RC?	−40	3·9	8·0	—		22·9	159
8	L	−40	23·5	T	?	2170	—	—
9	L	−35	21·8	T	37		—	—
10	L	−32	21·5	T	38		—	—
11	RC	−30	1·1	5·9	—		21·7	152
12	L	−25	21·1	T	96		—	—
13	RC	−24	2·8	11·2	—		25·1	148
14	RC	−15	21·0	T	34		—	—
Steel T								
1	RC	−68	16·8	T	—		—	—
2	L	−60	26·0	T	36		—	—
3	L	−65	6·5	18·0	—		28·2	78
4	RC	−50	3·3	5·2	—		28·0	63+

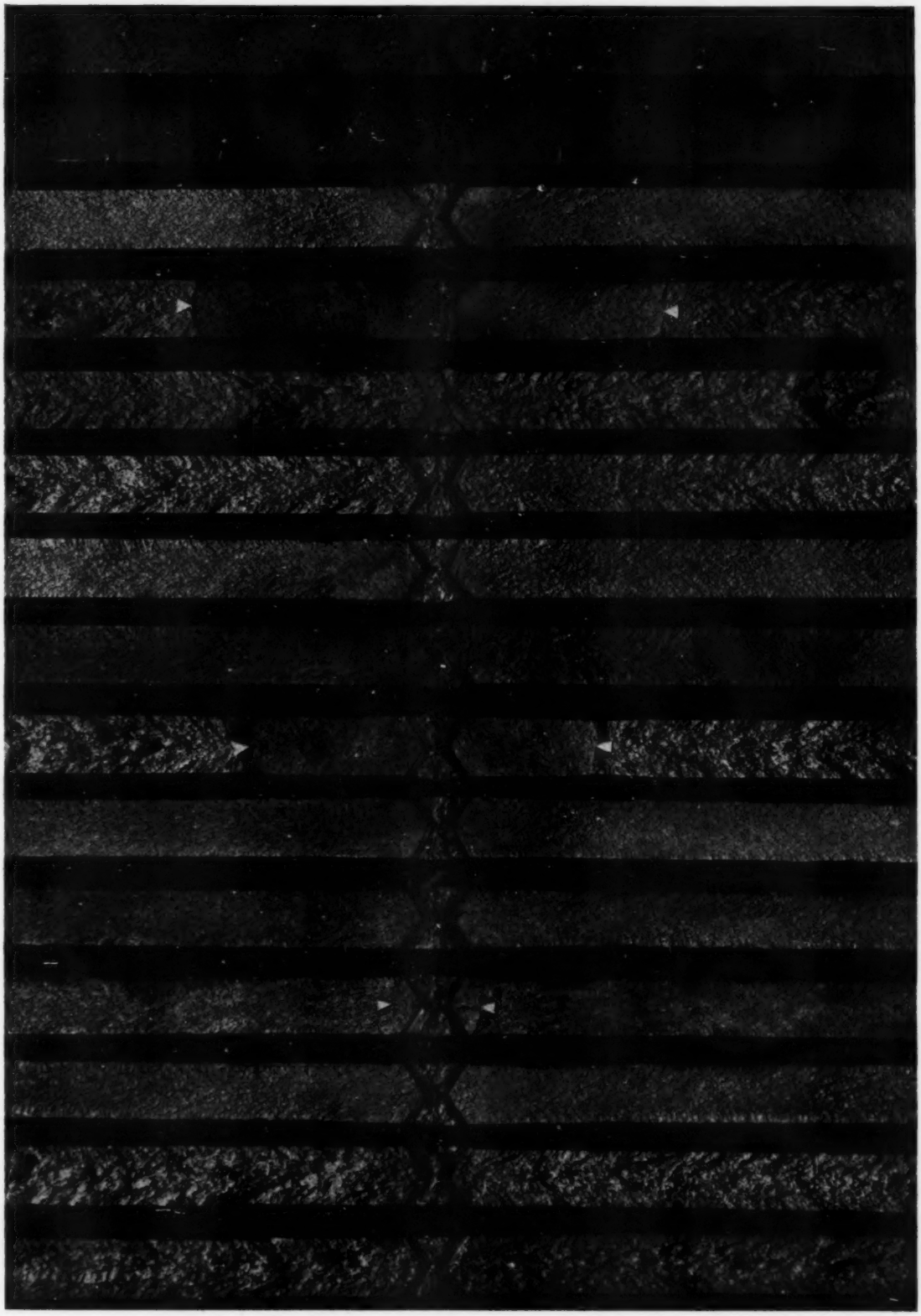
L = Root runs with low-hydrogen basic-covered electrodes E 615. Remainder welded with rutile-covered electrode E 319.
R = Weld deposit entirely with rutile-covered electrodes E 319.
C = Weld metal cross-section partially precracked in plane of sawcuts.
LD = As L, but weld metal drilled through 0·19 in. dia. on plane of sawcuts.
T = Through fracture without arrest.



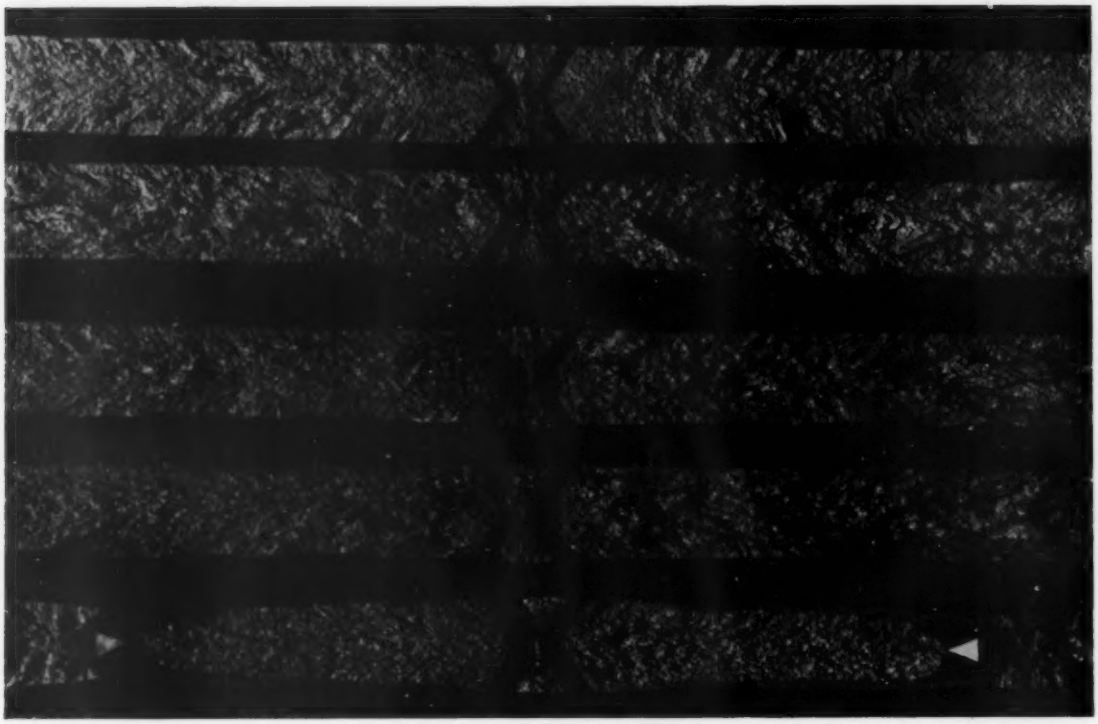
3—Fracture appearance: (a) *Steel P*



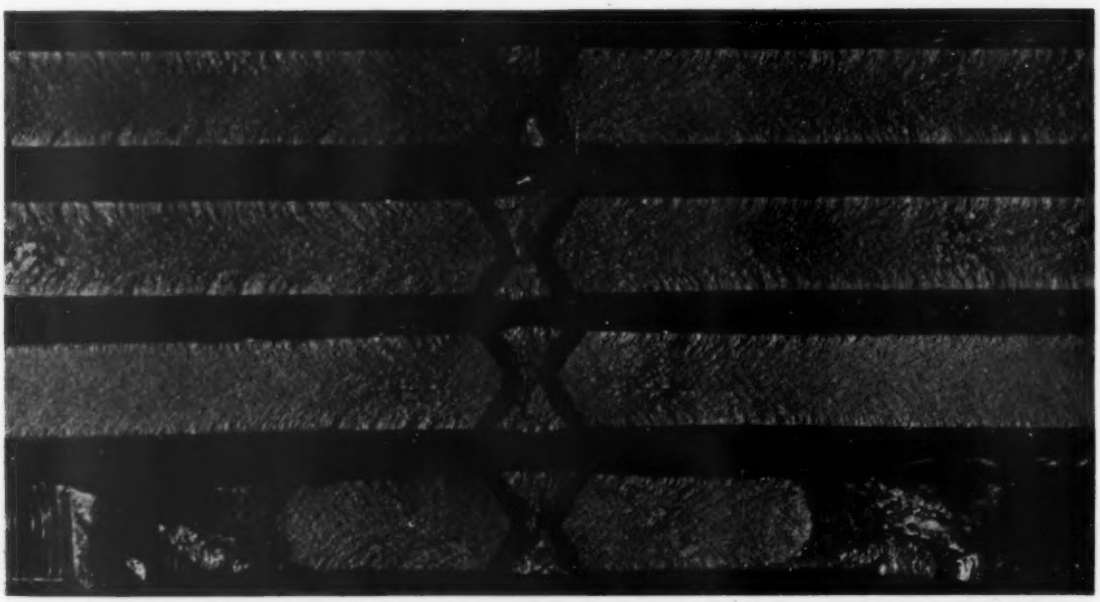
3—*Fracture appearance:* (b) *Steel P*



3—Fracture appearance: (c) *Steel Q*



3—Fracture appearance: (d) *Steel R*



3—Fracture appearance: (e) *Steel T*

3—Fracture appearance: (f) Steel S

Considerable differences in texture were noted in regard to the fractures in different steels, also at different points along the specimen, even for a single steel and testing temperature. Photographs of these fractured surfaces are presented in Fig. 3, from which certain features of the crack-starting notches may also be recognised.

In general, the load/extension curves for all specimens followed a set pattern (ref. 1, Fig. 5). The sequence is as follows:

(i) An elastic loading curve up to either arrested cracking or to yield
(ii) A further elastic loading at smaller slope following arrested cracking
(iii) A poorly defined general yield (ill-defined because of the gradual relief of residual stress by incremental plastic strain)
(iv) Extension to fracture at constant load.

Because of this limited range of behaviour plastic extensions to failure only are recorded in Table II. These have been defined as total extension to failure less the elastic component for the uncracked plate corresponding to the fracture load.

All the foregoing information is plotted graphically for each steel in Fig. 2, and in these diagrams the results of Charpy tests, both for energy absorption and crystallinity, the Robertson crack arrest, and Tipper and Pellini drop weight results have been superimposed. The plotted wide plate results expose anomalies as follows:

(*a*) Arrested crack lengths of 28 in. in steel *P* and 25 in. and 34 in. in steel *Q*, apparently due to an edge effect
(*b*) Extensions to fracture omitted in the case of two points with steel *P* and one with steel *S*; because of difficulties with the autographic recorder. The fractures, however, did not differ qualitatively from those of other specimens tested at similar temperatures.

Hardness traverses on transverse cross-sections of weld and parent plate were conducted at mid thickness and $\frac{1}{8}$ in. from the surface for steels *P*, *Q* and *S*. The results differed insignificantly from those given for a mild steel (ref. 1, Fig. 5), with respect to peak hardness and to distribution about the weld. They are given in detail in Fig. 4, for comparison with notch ductility information from the weld metal and heat-affected zones.

To facilitate comparison with the parent material, and with weld metals of similar characteristics studied by Watkinson,[10] Charpy test figures for energy absorption and crystallinity in heat-affected zones and weld metals concerned in the investigation are given in Table III. These results were obtained by testing groups of specimens (2 to 8 for each condition) at selected temperatures. The Charpy specimens were taken from wide plates which had fractured before yielding, the sampling positions being midway between the fractures and the specimen ends.

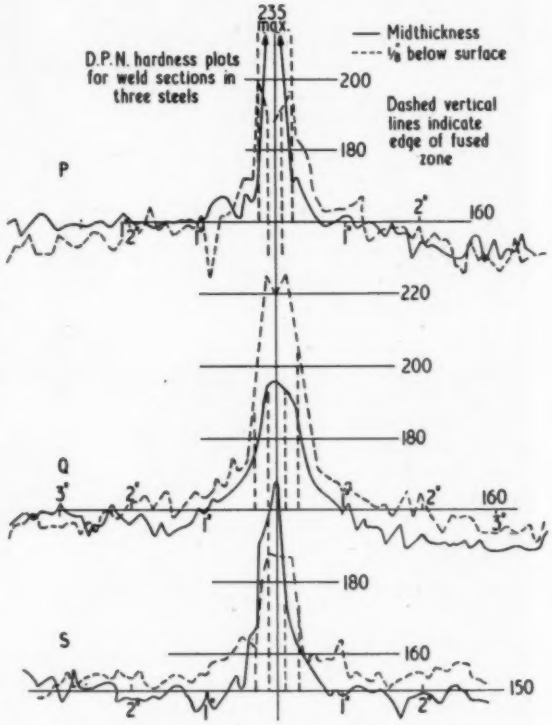
Fracture velocities were obtained from most specimens tested after installation of the timing

Table III

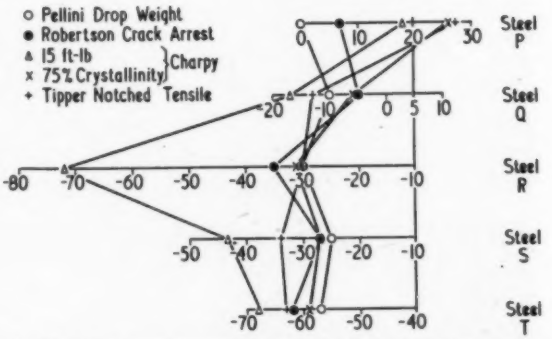
Weld metal and heat-affected zone Charpy transition temperatures

	Rutile covered Electrode Weld Metal			*Low-hydrogen basic-covered Electrode Weld Metal*		
Weld metal	−31	−19		−30	−15	
Steels	*P*		*Q*		*S*	
Parent material	+18	+27	−16	−6	−43	−27
$\frac{3}{4}$ in. from weld centre	+16	+33	0	+7	−38	−27
$\frac{1}{8}$ in. from weld centre	+31	+42	−10	+16	−47	−27

Transition temperatures (°C.) for 15 ft-lb energy absorption on left hand side and 75% crystallinity on right hand side.



4—*Hardnesses of welds and heat-affected zones*



5—*Transition temperatures compared with highest temperature (°C.) for any appearance of cleavage in fracture of notched and welded wide plate in as-welded condition*
(Temperature scales displaced horizontally so as to place wide plate reference temperature on common vertical intercept)

equipment, although a few records were lost through premature fracture of the gauge wires as the plates yielded. The available results are given in Table II.

Discussion

Critical temperature

It is clear from the results given in Table II and Fig. 2 that the general trend of behaviour of the test plates is similar to that previously shown (ref. 1, Fig. 8). However, the paper of that reference concluded with the suggestion that the low-stress type of through fracture was confined to a critical temperature, *i.e.*, it was not apparent at low or high temperatures. Although this was logical, as supported by the results then available, it is now apparent that low-stress through fracture can occur over a wider temperature interval. The results for steels *P*, *Q*, *R* and *T* suggest that some such fractures would be expected even at temperatures lower than could be achieved with the existing cooling arrangements. This conclusion was also reached by Kihara and Masubuchi.[7]

Crack propagation

The relative occurrence of low-stress through fractures or arrested short cracks seems fairly clear.

Sufficient tests were conducted with steels *P* and *Q* to show that no low-stress through fractures would be experienced either (*a*) at temperatures significantly above the Robertson crack arrest temperature, or (*b*) at applied stress levels significantly below the Robertson crack arrest stress for the appropriate temperature. However, attention should again be drawn to the three results for steels *P* and *Q*, where fractures of considerable length occurred below the Robertson arrest temperature but at applied stresses down to less than half the crack arrest stress. It is believed that in these instances arrests occurred because of the influence of an edge effect. This is discussed in relation to crack extension force in the Appendix.

Electrode type

It is of interest to note the differences in initiation behaviour, particularly with specimens of steels *P*, *Q* and *S* having different weld deposits. In general, higher applied stresses for initiation were required for specimens welded with low-hydrogen basic-covered electrodes. On closer inspection, as may be seen from the photographs of fracture surfaces in Fig. 3, the lower stress initiations are associated with specimens where the weld deposit cracked partially across immediately after welding. This was demonstrated by the presence of an oxidation deposit on the precracked surfaces, and could easily be distinguished from shear or some other fracture mode by the presence of precracking and a shear lip, side by side, on the same specimen. The precracking experienced was as follows:

	Rutile	*Low-hydrogen basic*
Precracked	21	7
Uncracked	0	29
Doubtful	1	0
Drilled	0	2
Total	22	38

This very marked difference in behaviour between the two types of weld metal is obviously associated with a temperature at least as high as the interpass temperature during welding. Whilst the possibility of hot cracking cannot be eliminated, it is thought to be unlikely, since the freshly exposed oxidation was observed to be only of temper colour type. Moreover, so called 'cold' cracking has frequently been associated with the fissuring seen to occur in the presence of diffusible hydrogen, so that a marked difference in fissuring behaviour would be expected with electrode coverings of the types used. For instance, Watkinson[10] has tested butt welded joints in 1 in. thick semi-killed mild steel plates with these electrodes and has obtained the following fissure counts on polished and etched longitudinal sections of the welds:

	Rutile	*Low-hydrogen*	
Downhand	56·3	34·5	Microfissures per sq.in.
Horizontal/vertical	32·7	0	
15 ft-lb	−27°C.	−24°C.	Charpy V notch on downhand deposits
50% crystallinity	− 4°C.	+15°C.	

Significantly less fissuring was shown with the low-hydrogen weld metal, and there was no significant difference between the transition temperatures shown in the Charpy test results. The notch ductility of the deposited weld metal is midway between those of steels *Q* and *S*. The few check tests on specimens from this investigation reported in Table III confirm this conclusion. Vaughan and De Morton[11] have demonstrated the manner of growth of cleavage cracks in steel specimens charged with hydrogen, and there is little doubt that the microfissures which may be observed in polished and etched cross-sections could grow into major cracks through the action of the concentrated strain occurring between the sawcuts in the wide plate specimens.

With the exception of only three specimens, it has been possible to draw dividing lines on the fracture stress/temperature diagrams (Fig. 2) to separate the fracture stress behaviour of precracked and uncracked specimens and so, to a large extent, of specimens welded with rutile and low-hydrogen electrodes. Furthermore, in two cases with steel *P*, it was possible to simulate the behaviour of rutile welded specimens, while using low-hydrogen electrodes, by drilling away the otherwise sound weld metal in the planes of the sawcuts. This would suggest that the area of the flaw normal to the applied load, as influenced by the precracking, is an important factor in controlling initiation stress, rather than any effect which might have been caused by hydrogen absorption at the roots of sawcuts. Further, it would seem that the degree of precracking of rutile and low-hydrogen type weld metals has a greater effect on specimen strength than notch ductility measurements of Charpy type would indicate.

The placing of more tests with precracked specimens in the higher temperature range (Fig. 2) corresponds with efforts to measure the highest possible temperatures at which brittle fractures could occur.

Heat-affected zones

The shifts of Charpy transition temperature for the heat-affected zones, which may be deduced from

Table III, are not particularly large and are negligible for steel *S*. However, it is clear that the material from the region of the sawcut notches must have been embrittled by the heat and plastic flow from welding, because of the ease with which initiation later took place. It can only be concluded that Charpy tests on heat-affected zone material taken at random are insensitive to the latter effect, and that specimens would have to be taken from the notched zones themselves to show any effect.

Shock initiation

It has been suggested that in the type of test now under discussion, low-stress fracture initiations may occur as a result of a shock effect from sudden severance of the weld metal. Careful examination of the fracture surfaces does not positively confirm or disprove this, but it would have been extremely unlikely in some of the tests, either because the weld metal possessed greater ductility (as demonstrated by large shear lips) than the parent material, or because the weld metal ligament had previously been almost severed by precracking. The three exceptional specimens mentioned, in which unusually low stress fractures originated without precracking, might have failed as a result of a shock effect from primary cracking of the weld metal. It is significant that the fractures all occurred below −30°C., where the weld metal would have been in a more notch brittle condition than the plates *Q*, *S* and *T* in which the fractures occurred. It is concluded that shock initiation may sometimes occur, but that the effect is of no greater significance than shock initiation of a fracture from one notch in a Tipper specimen following plastic strain initiation from the notch on the opposite side. This phenomenon occurs frequently, with cracks meeting, or overlapping, near the centre of the specimen.

Appearance of fracture in the wide plates

For the purpose of correlation with small-scale tests it is of interest to examine fracture appearance in the wide plate specimens. Since, in general, there was insufficient load and extension capacity available in the test rigs to permit check tests in the temperature range for ductile behaviour, as conducted by Kihara and Masubuchi, the reference temperature has been defined as that at which the only brittle fracture occurring is arrested when short, and is initiated following general plastic extension. Such fractures were obtained in steels *P* and *R*. The arrested fractures in these specimens could not be reinitiated on further loading without reducing the plate temperature. Although the reference temperatures could not be located precisely for the remaining steels, estimates are given in Fig. 2, based on (*a*) the highest temperature for a low-stress fracture initiation and (*b*) the plastic extension, fracture roughness, and shear lip width at the plate surfaces of the specimens tested at the highest temperatures. The behaviour has been compared on these criteria with that for steels *P* and *Q*. The degree of conformity is such that the estimates are believed to be correct to within ±3°C.; the assessment can be checked from information given in this report.

Small test correlation

For the purpose of comparison with a selected group of small-scale test criteria, the wide plate reference temperature has been taken as the basis for the graphical presentation in Fig. 5, which shows the temperature displacements for other criteria on each steel. The chosen criteria are as follows:

Charpy 75% crystallinity Tipper 50% crystallinity	Fracture appearance
Charpy 15 ft-lb energy	Energy
Pellini drop weight nil-ductility[12]	Ductility in the presence of a notched weld

Other fracture appearance criteria are available, notably from Van der Veen slow bend, and 2 ft wide Tipper notched tensile tests, but are excluded from Fig. 5 to avoid confusion. This is acceptable, since in most cases the Charpy and Tipper fracture appearance test results are already in close agreement.

It is recognised that the present selection of steels is not wide enough to show the full extent of anomalies which can occur.[13] In spite of this, tentative conclusions may be drawn in regard to correlation, and a general observation may be made that in most cases the wide plate reference temperature is higher than others.

Bearing in mind the similarity of the test pieces, with deposited weld metal stressed in tension in the direction of deposition, the transverse notch, and the application of limited bending strain, it is not surprising that agreement should exist between the Pellini drop weight transition temperature and the reference temperature as defined for the wide plate test. The fact that the latter is from 15° to 20°C. higher may be regarded as due to the more severe notch and the additional cooling restraint during and after welding resulting from greater plate width.

It is also interesting that nearly as uniform a correlation should exist between the Robertson crack arrest temperature and the wide plate reference temperature, although the tests are ostensibly concerned with different properties. It has already been noted that no low-stress through fractures occurred at temperatures above the Robertson crack arrest temperature. With the exception of steel *P*, for which a significantly higher transition temperature appears with the two fracture appearance criteria, the latter agree closely not only between themselves but with the Pellini drop weight, Robertson crack arrest, and wide plate reference temperature. It is possible that the inconsistency in the case of steel *P* is associated with greater relative embrittlement in this steel from large plastic strain preceding fracture. The Charpy and Tipper tests used for the fracture appearance assessment differ from the Pellini, Robertson, and wide plate tests essentially in the single feature of degree of pre-fracture yield, which is significantly greater in the former cases (Fig. 5).

In relation to the other criteria, 15 ft-lb energy absorption in the Charpy test shows a significantly lower transition temperature for steel *R*. Conversely, this criterion shows a rather high transition temperature for steel *P*. Thus the energy criterion is the most irregular when compared in this way. Nevertheless, energy absorption is significant. The attribution to steel *R* of a low 15 ft-lb transition temperature is equivalent to describing it as having high energy absorption; similarly, steel *P* has a low energy absorption. It may also be noted that there was a

preponderance of high-load wide plate fractures with steel *R*, and of low-load fractures with steel *P*.

It is evident that a simple explanation of these anomalies is not to be found from the more elementary properties recorded, such as chemical composition, stress/strain data, or microstructure. To go much beyond these is outside the scope of this report, but the accumulation of data has provided an opportunity for such a study, and this is in hand.

Stress relieving

In assessing the behaviour of the welded plates of the low-transition temperature steels *Q*, *R*, *S*, *T*, it is useful to bear in mind the comparable results of Kennedy[14] for similarly tested plates of the semi-killed higher-transition temperature steel *P*, which had received a furnace stress-relief treatment at 600° or 650°C. before loading (Table IV).

From the viewpoint of crack initiation, the stress-relieved specimens of the relatively brittle steel *P* gave a performance at −56°C. superior to that of as-welded specimens of any of the other steels. It would be of value to study the improvement following stress relieving of the remaining steels.

Crack velocities

The measured brittle crack velocities given in Table II, mainly for steel *P*, show no correlation with temperature, stress level, or previous cracking. The average crack velocity for steel *P* of 3,250 ft/sec is somewhat greater than any of the values for steels *Q* and *S*, and is substantially less than a theoretical[15] limiting velocity for steel of 6,300 ft/sec. It is probable that the low measured velocities may be related to the degree of plastic yield taking place along the fracture surfaces as propagation proceeds, and introducing a secondary limitation owing to the low velocity of plastic wave propagation. Although a relationship between fracture texture and velocity might have been expected, it is evident from the comparison between a smooth fracture (*Q* 10) and rough fractures (*Q* 4 and 9) that the effect, although present, is not pronounced. On the other hand, there is a strong correlation between the average tensile stress at which fracture takes place and the degree of roughness, as may well be seen in the specimens of steels *Q* and *S* (Fig. 3). The effect is compatible with variation of stress gradient, itself related to crack extension force. With high applied stress, the stress gradient is invariably low and a large volume of metal is affected by cleavage as the crack progresses. This gives rise to a rough texture, and *vice versa*.

Conclusions

(1) Out of a total of 60 notched and welded wide plate specimens from two semi-killed and three fully-killed low-carbon steel plates 1 in. thick, tested at temperatures from 35°C. below the Robertson crack arrest temperature for each steel up to the highest temperatures at which any vestiges of brittle fracture could be observed, 35 fractured either at low applied tensile stress, or with no significant prefracture plastic extension. Of these, 22 failed at an applied stress less than one third yield point, and 12 fractures passed through the plates without crack arrest.

(2) Although an increase of fracture strength with increased temperature could be observed with those steels in which sufficient numbers of specimens were tested, a pronounced effect was confined to a range of a few degrees above the Robertson crack arrest temperature. Within this range, minimum applied stresses for crack initiation increased from very low values up to yield point; below it a temperature effect was virtually absent. Taken as a group, the low-stress through fractures were distributed evenly over the lower temperature ranges, none taking place at temperatures higher than the Robertson crack arrest temperature.

(3) All specimens with test welds deposited entirely with E 319 (BS.1719) rutile-covered electrodes were precracked over part of the weld metal plane between the sawcuts. Oxidation colouring showed that this took place soon after weld metal deposition. A high proportion of specimens in which the root runs were deposited with E 615 low-hydrogen basic-covered electrodes did not precrack. The fracture strength of the wide plate specimens in which precracks were later found was significantly lower than for the others; transition temperatures for low-stress crack initiation were higher for the precracked specimens. The effect could not be correlated with any difference in Charpy transition temperatures for the two types of weld metal, but contemporary evidence is quoted to show a correlation with micro-fissuring.

(4) The highest temperature at which short brittle cracks could be initiated following fully plastic strain in the wide plate specimens was about 15–20°C. above

Table IV

Effect of stress relief on fracture characteristics

Steel	*Electrode Covering*	*Condition*	*Temperature, °C.*	*Prefracture Extension, %*	*Fracture Stress, tons/sq.in.*	*Type of Fracture*
P	Rutile	Stress relieved	−25	1·49	15·0	Through
	Rutile	Stress relieved	−56	0·69	16·6	Through
Q	Low-hydrogen	As welded	−11	1·36	18·0	Arrested*
	Low-hydrogen	As welded	−35	None	5·0	Through
R	Low-hydrogen	As welded	−10	0·13	20·5	Arrested*
	Low-hydrogen	As welded	−60	None	9·8	Through
S	Rutile	As welded	−15	0·34	21·0	Through
	Low-hydrogen	As welded	−56	None	2·5	Arrested*
T	Rutile	As welded	−50	None	3·5	Arrested*
	Rutile	As welded	−68	None	16·8	Through

* For secondary fracture data, see Table II.

the Pellini drop weight nil-ductility transition and the Robertson crack arrest temperatures for the parent materials. The latter were also close to the 75% and 50% crystallinity figures respectively for the Charpy and the Tipper notched tensile tests, except for the semi-killed steel *P*, of ordinary structural quality, where these were about 25°C. higher, an effect attributed to embrittlement from large prefracture strain in the Charpy and Tipper tests.

(5) Although 15 ft-lb energy absorption in the Charpy test did not correlate well with any observed transition temperature behaviour in the wide plate tests (with steels *P* and *R* as extreme cases), a subsidiary correlation showed that the steels of high energy absorption gave a preponderance of high-stress wide plate fractures and *vice versa*.

(6) The resistance of furnace stress-relieved semi-killed steel *P* specimens to brittle fracture initiation at low temperatures was superior to that of as-welded specimens from any of the other steels, although the Pellini drop weight transition and Robertson crack arrest temperatures for the latter were 10–57°C. lower.

Acknowledgments

The work was instigated and followed with close interest by Dr. H. G. Taylor, former Director of Research, and by Dr. R. Weck, formerly as Chairman of the guiding Panel and, later, as Director of Research. Advice and help from all members of the B.6(FE.19) Committee of B.W.R.A. and from the author's colleagues, notably Mr. P. H. R. Lane, is also freely acknowledged. Generous supplies of steel *P*, *Q* and *S*, specially documented in manufacture, were made available by the Heavy Steel Makers Association; steels *R* and *T* were provided in exchange by the Admiralty, and use has been made of the extensive test data obtained on all the steels by the Admiralty Advisory Committee on Structural Steel. Appreciation is expressed to these organisations for their support and co-operation.

Until his departure from the Association the work was entirely organised and reported by Mr. G. Coates; manufacture of the specimens, and the development of techniques to eliminate distortion in their preparation, were under the charge of Mr. E. O. Lawrance, and Mr. B. Wakefield was responsible for all phases of testing and recording of information. Grateful thanks are accorded to them and to their assistants.

Opinions expressed in the report are the responsibility of the author alone.

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APPENDIX I

Crack Arrest Edge Effect in a Square Plate in Tension

By Mrs. M. S. Toms, B.SC., A.R.C.S.

For an infinite plate of unit thickness, under conditions of plane strain, with cracks of length $2a$ repeated along the x axis (Fig. 6) at intervals l, the following formulae are given by Westergaard (eq. 9).[16]

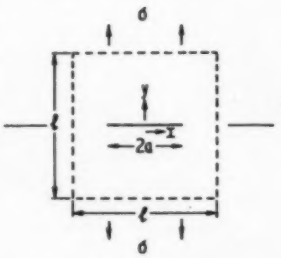
$$\text{Stress function } Z=\sigma\left[1-\frac{\sin^2\pi\left(\frac{a}{l}\right)}{\sin^2\pi\left(\frac{z}{l}\right)}\right]^{-\frac{1}{2}}$$

$$\text{and } 2G\eta=2(1-\mu)\,Im.\overline{Z}=y.Re.Z$$

where $z=x+iy$
η = displacement in the y direction
σ = biaxial tension stress
μ = Poisson's ratio
G = Modulus of rigidity
$\overline{Z}=\int Z dz$

$$\text{Integrating } Z,\ \overline{Z}=i\,\frac{l\sigma}{\pi}\cosh^{-1}\left[\frac{\cos\pi\left(\frac{z}{l}\right)}{\cos\pi\left(\frac{a}{l}\right)}\right].$$

Considering now the top edge of the plate shown in Fig. 6, η was calculated as a function of a/l at two



6—*Mathematical model of problem: an infinite plate with repeated cracks*

points on the edge, the centre and the right-hand corner, giving

$$\eta(x=0,y=\tfrac{1}{2})=(1+\mu)\,\frac{l\sigma}{E}\left\{\frac{1-\mu}{\pi}\cosh^{-1}\left[\frac{2\cosh^2\left(\frac{\pi}{2}\right)}{\cos^2\pi\left(\frac{a}{l}\right)}-1\right]\right.$$

$$\left.-\frac{1}{2}\,\frac{\sinh\frac{\pi}{2}}{\sqrt{\left[\sinh^2\left(\frac{\pi}{2}\right)+\sin^2\left(\frac{\pi a}{l}\right)\right]}}\right\}$$

$$\text{and } \eta\left(x=\frac{l}{2},y=\frac{l}{2}\right)=(1+\mu)\frac{l\sigma}{E}\left\{\frac{1-\mu}{\pi}\cosh^{-1}\left[\frac{2\sin h^2\left(\frac{\pi}{2}\right)}{\cos^2\left(\frac{\pi a}{l}\right)}+1\right]\right.$$

$$\left.-\tfrac{1}{2}\frac{\cosh\frac{\pi}{2}}{\sqrt{\left[\sinh\left(\frac{\pi}{2}\right)+\sin^2\left(\frac{\pi a}{l}\right)\right]}}\right\}=(1+\mu)\frac{l\sigma}{E}f\left[\frac{a}{l}\right] \quad \ldots\ (1)$$

These expressions produce very similar curves. The expression for η at the corner of the plate was taken as an approximation everywhere along the top edge, the error involved being nowhere more than 4%.

For unit thickness, the energy stored in the plate is $\sigma l\eta_0=W$. If σ_0 and η_0 are the values of σ and η just before the crack begins:

$$\frac{\sigma}{\sigma_0}=\frac{\eta_0}{\eta}, \text{ so that } W=\eta_0\frac{\eta_0}{\eta}\,l\eta_0=\frac{l\sigma_0}{\eta}\eta_0^2=\frac{l^2\sigma_0^2\,l}{8E^2\eta} \quad \ldots\ (2)$$

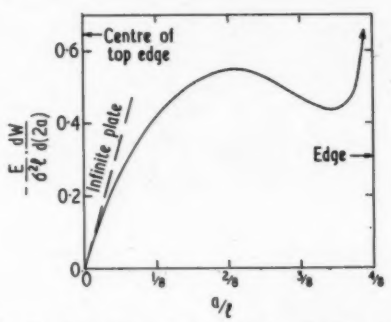
The rate of release of energy with crack length, equal to the crack extension force $\mathscr{G}$, is

$$-\frac{dW}{d(2a)}=\frac{\sigma_0^2\,l}{E}\cdot\frac{1}{8(1+\mu)}\cdot\frac{1}{f^2\left(\frac{a}{l}\right)}\cdot\left\{2(1-\mu)\sinh\left(\frac{\pi}{2}\right).\tan\left(\frac{\pi a}{l}\right)\right.$$

$$\left[\sinh^2\left(\frac{\pi}{2}\right)-\cos^2\left(\frac{\pi a}{l}\right)\right]^{-\frac{1}{2}}-\left[\left(\frac{\pi}{2}\right)\cosh\left(\frac{\pi}{2}\right)\sin\left(\frac{\pi a}{l}\right)\cos\left(\frac{\pi a}{l}\right)\right]$$

$$\left.\left[\cosh^2\left(\frac{\pi}{2}\right)-\sin^2\left(\frac{\pi a}{l}\right)\right]^{-\frac{3}{2}}\right\} \quad \ldots\ (3)$$

The expression was differentiated again and the zero of $\frac{d^2W}{d(2a)^2}$ was found graphically, giving a minimum rate of release of energy with crack length at $\frac{14}{32}>\frac{a}{l}>\frac{13}{32}$. The shape of this curve and the position of the minimum are shown in Fig. 7. The minimum value of $\frac{dW}{da}$ is $0{\cdot}88\frac{\sigma_0^2 l}{E}$.



7—*Crack extension force* versus *length of crack*

The analysis thus presented does not take residual stress into account, but in the latter respect the butt weld case in an infinite plate was discussed in reference 1. To calculate whether a crack will be arrested in the residual stress zone or at the plate edge, comparison may be made between the respective minimum values of crack extension force:

$$\mathscr{G}_1=\frac{8P\sigma}{E} \text{ (Reference 1, equation 7)} \quad \ldots\ (4)$$

$$\mathscr{G}_2=0{\cdot}88\,\frac{\sigma^2 l}{E}.$$

Arrest would not be expected to occur at the edge unless $\mathscr{G}_2<\mathscr{G}_1$ or $\sigma<\frac{9{\cdot}1P}{l}$. Figure 13 of reference 1 suggests that a typical value of the weld residual load P would be 27 tons per inch, giving $\sigma<6{\cdot}8$ tons/sq.in. Examination of the experimental results in this report suggests that edge arrests only occurred for values of $\sigma<4$ tons/sq.in. The agreement may be considered reasonable.

APPENDIX II

Examination of Steels and Fracture Origins

By P. Whitaker

It is confirmed that these steels have been examined with respect to McQuaid-Ehn grain size and chemical analysis, and steels *P*, *Q*, and *T* with respect to the micro-structure at the base of the jeweller's saw cuts. From each of the steels *P*, *Q*, and *T*, two fractured test pieces were received (Fig. 1), one made with rutile covered electrodes E.319 (BS.1719), and one with low-hydrogen basic-covered electrodes E.615.

Chemical analysis

Determinations of H_2, N_2, soluble Al and Sn were made on all five steels, and Ti determination on steel *S* only.

The following results confirm the low soluble aluminium content of steel *S*. The presence of approx. 0·005% Ti suggests that the fine inherent grain size may be due to the use of special steelmaking deoxidants.

Chemical analysis

Sample Marked	*Hydrogen, ml/100 g*	*Nitrogen, %*	*Soluble Al,%*	*Tin, %*	*Titanium, %*
P.7	0·5/0·5	0·0050	0·004	0·020	
Q.7	0·1/0·2	0·0050	0·003	0·004	
R	0·1/0·2	0·0040	0·074	0·020	
S	0·1/0·1	0·0050	0·008	0·021	0·005 approx.
T.3	0·1/0·1	0·0050	0·081	0·020	

McQuaid-Ehn grain size

Steel	*Maximum*	*Author Minimum*	*Average*	*B.W.R.A.*
P	1	6	4	2
Q	1	4	2–1	4–5
R	5	8	7	7
S	3	8	6	6
T	4	8	7	7

The generally fine inherent grain size of steel *S* is confirmed but it contains isolated large grains of up to Grade 3.

Steels *P* and *Q* give results opposite to those drawn from the test data supplied by the Admiralty Materials

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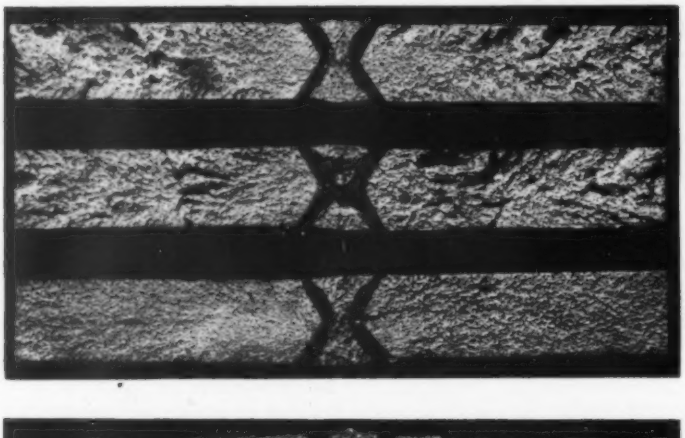
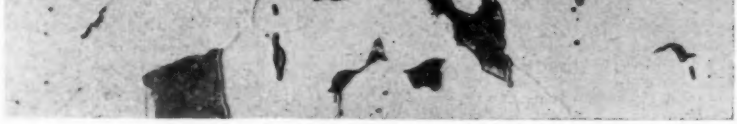
Report B6/9/60 of the British Welding Research Association, circulated to members in March 1960.

Mr. Whitaker is with Stewarts and Lloyds Ltd. 631



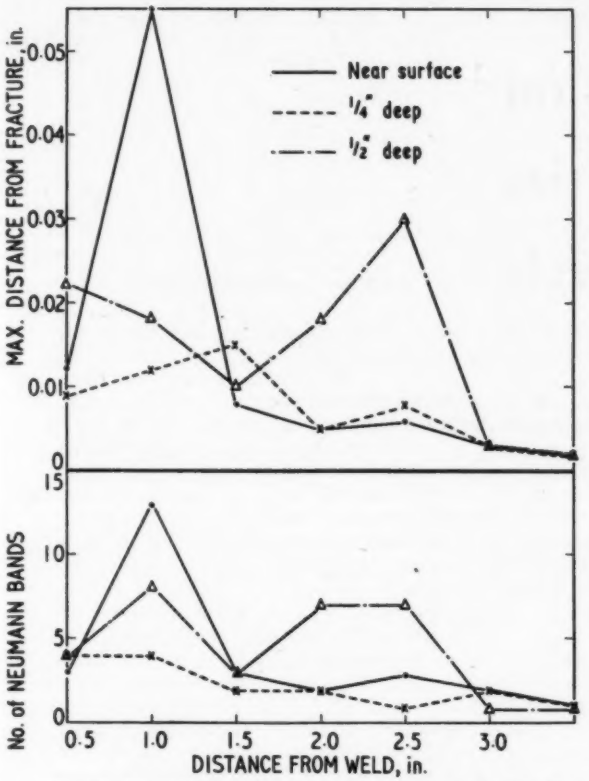
1—*Appearance of fractures in test pieces received*



(a)

2—*Sections through base of saw cut in test piece P.18, showing*
(a) *heavily deformed material;*
(b) *diversion of non-metallic inclusions. Unetched* ×500

(b)



3—*Number of Neumann bands and maximum distance from fracture in test piece P.18*

Laboratory and quoted by B.W.R.A. Further information is being sought.

Microstructure at base of saw cut

Sections normal to the plate surface, and therefore at an angle of about 30–40° through the base of the saw cut, were taken from each of the six fractured test pieces.

In all six sections a distortion of the structure was found at both the base (Fig. 2*a*) and the sides of the saw cut. The thickness of this deformed layer was up to 0·0007 in. and in some cases it was associated with diverted non-metallic inclusions (Fig. 2*b*).

In the heat-affected zones of the weld this work-hardened structure had recrystallised to give a narrow band of very fine grains.

Hardness of deformed layer

Test piece P.18

	Load	*Deformed Layer*	*Normal Structure*
Micro	20 g	265–330 D.P.N.	166–212 D.P.N.
Macro	30 kg	—	156–169 D.P.N.

The material at the base of the saw cuts had been work-hardened to the maximum capacity of the steel.

Neumann band counts

Test piece P.18

At positions approx. 0·025, 0·25, and 0·5 in. below the plate surface fields 0·015 in. wide were examined for a distance of 0·2 in. from the fracture face.

The results of seven sections taken at approximately ½ in. intervals from the apex of the saw cut are shown in Fig. 3.

Strain etching of some of the sections is being carried out and will be reported later.

Effect of Plastic Strains on Mechanical Properties of Five Steels

By C. F. Tipper, SC.D.

The effects of plastic strain, ageing, and stress relieving have been studied by means of notch impact and tensile tests on five 1 in. mild steel plates.

Strains just exceeding the yield point (4–5%) shifted the Charpy V-notch curves to higher temperatures and the 15 ft-lb transition by from 20° to 30°C. Stress relieving at 650°C. brought the curves back towards the original values, but only in one steel was recovery nearly complete. Samples cut transverse to the direction of rolling and straining showed less recovery.

Introduction

THESE experiments were undertaken initially with the object of explaining the different response to static and dynamic tests in the survey of test methods carried out by the Admiralty Advisory Committee on Structural Steel on five 1 in. mild steel plates. It was thought that some plastic strain and ageing might raise the transition temperature during the static tests. It was also thought that plastic strain, followed by ageing, such as must necessarily occur in the neighbourhood of welds, might contribute to the spontaneous initiation of short cracks in the wide plate tests of the same steels made by Dr. Wells. Cracks of this type are usually attributed to the residual strains which occur through welding, and they extend to a distance beyond that where any visible change in the microstructure can be detected. On the other hand, the appearance of Luders bands in the scale at a considerable distance from welds is not uncommon and is a proof that the material has yielded beyond what is usually described as the heat-affected zone. It appeared worthwhile to note the effect of plastic strains just exceeding the yield point on the transition temperatures of the plates as determined by means of V-notch Charpy tests, and then to apply a stress relieving treatment, to see how much recovery occurred.

Experimental Results

Full particulars of the five steels are given in Dr. Wells's report* B6/1/58 and in the AACSS Report P2.† Brief descriptions are as follows:

Designation	*Description*
P	Ordinary mild steel, 0·18% C, 0·54% Mn, semi-killed, as rolled.
Q	0·15% C, 1% Mn, semi-killed, as rolled.
R	0·12% C, 1·4% Mn, grain-controlled, normalised.
S	0·15% C, 1% Mn, grain-controlled, normalised.
T	0·15% C, 1·4% Mn, grain-controlled, normalised.

Of these, only *P* and *Q*, being semi-killed, might be expected to show any strain age embrittlement, and that only slightly, while all would be work hardened if strained into the plastic range.

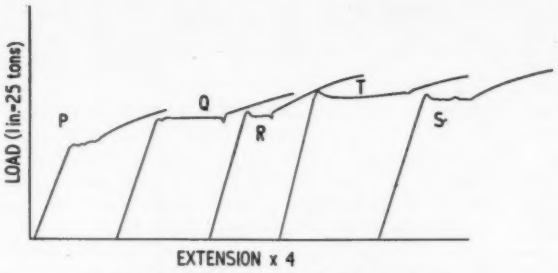
Large parallel-sided test pieces, 18 in. long by 3 in. wide, and of full plate thickness, were machined from these plates and strained plastically until the overall extension was approx. 5%. This ensured that the yield was completed while the extension in the parallel portion was uniform, being checked by dividers on 2 in. gauge lengths. Load/extension curves are shown in Fig. 1. Yield shape varied considerably over the five steels.

Most of the test pieces were machined from the uniform portion in the direction of straining, but a few were also cut transversely. These consisted of Charpy V-notch specimens, and also tensile test pieces for determining yield, ultimate stresses, and ductility as a measure of (*a*) the work hardening produced by the straining, and (*b*) recovery due to the subsequent treatment.

After machining, all test pieces were treated in a salt bath for 1 hr at 200°C. One set was tested after

* See p. 259, this issue.
† Report P2 of the AACSS 1960, H.M.S.O.

Report B6/8/60 of the British Welding Research Association, circulated to members in March 1960.
Dr. Tipper was formerly in the Engineering Department of Cambridge University.



1—*Load/extension curves for the five steels*

this treatment and one set after further heating at 650°C. for 1 hr. One tensile test piece in the as-rolled condition from each of steels *P*, *Q*, and *T* was also heated at 650°C. to assess the stress relieving treatment. As there was a small amount of material left from the strained steels *Q* and *T*, this was heated at 850°C. and air cooled, Charpy V-notch test pieces being cut after heat treatment.

The most comprehensive study was made of plates *P*, *Q*, and *T*, since these were the most likely to show differences in response to the treatment applied, and did in fact show the greatest scatter in transition temperatures in the AACSS survey. Plates *S* and *R* were added later to complete the series. The impact tests were made on the Charpy machine at Abington so as to remove one possible source of discrepancy in comparing these results with those made under the testing scheme for the AACSS Panel. The number of test pieces available was insufficient to plot mean curves with accuracy, but since the trend was the same for all five steels, broad conclusions can be drawn. The impact test results are plotted in Figs. 2–9 and are summarised in Table I. The tensile test results made on 0·25 in. dia. cylindrical bars on a Hounsfield Tensometer are presented in Table II.

Table I

Charpy V-notch 15 ft-lb transition temperatures

Steel	*Condition*	*Long. Direction, °C.*	*Trans. Direction, °C.*
P	As rolled	16	19
	Strained	46	38
	Stress relieved	20	38
Q	As rolled	−18	−13
	Strained	11	5
	Stress relieved	−10	0
R	As rolled	−70	
	Strained	−20	
	Stress relieved	−30	
S	As rolled	−44	
	Strained	−18	
	Stress relieved	−40	
T	As rolled	−68	−66
	Strained	−32	−30
	Stress relieved	−32	−40

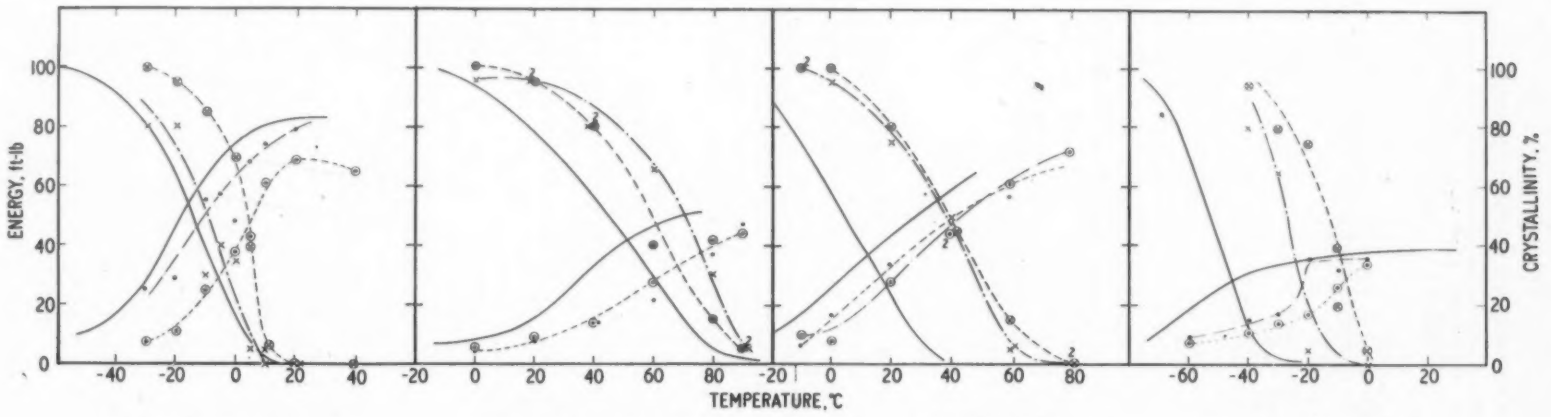
Discussion of Results

All tests made on material in the direction of rolling and straining showed a shift in the 15 ft-lb Charpy V-notch transition to higher temperatures ranging from 26° to 40°C., with a general decrease in energy absorption when compared with the untreated material at the same temperatures. In samples cut transversely there was also a decrease in energy and shift of the curves, the proportional change being difficult to

Table II

Hounsfield tensile tests

	Steel and Treatment	*Yield Stress, tons/sq.in.*	*Ultimate Stress, tons/sq.in.*	*Elong., %*	*Red. in Area, %*	*Hardness, D.P.N.*
Test pieces cut in direction of straining						
P	As rolled	Yield not recorded	25·6	41	62–65	119
		U L				
	As rolled, heated 1 hr 650°C.	14·6 14·0	26·5	40	60–61	
	Strained, aged	25	28·7	30	58–60	157
		24·9	28·8	28	62	
		24·8	28·8	29	62	
	Strained, aged, heated 1 hr 650°C.	17·75 17·3	27·7	31	48–50	129
Q	As rolled	15·9 15·4	27·2	42	70–72	123
	As rolled, heated 1 hr 650°C.	16·6 16·3	26·9	43	62–63	
	Strained, aged	25·6	30·4	30	70	158
		24·8	29·6	33	72	
		24·2	27·7	35	70	
	Strained, aged, heated 1 hr 650°C.	19·2 18·8	27·7	36	55–56	132
T	As received	21 20·4	31·65	34	68–70	145
	Heated 1 hr 650°C.	20·9	30·8	39	65–68	
	Strained, aged	28·4 28·15	32·4	33	72	171
		28·15 27·9	31·9	34	71	
		27·8	33·3	34	68	
	Strained, aged, heated 1 hr 650°C.	24 23·6	31·3	34	60–62	145
Test pieces cut transverse to direction of straining						
P	Strained, aged	20	29·5	26	52–55	155
	Strained, aged, heated 1 hr 650°C.	24	33·5	22	52–55	185
Q	Strained, aged	24	30·5	31	68–70	155
	Strained, aged, heated 1 hr 650°C.	22	31	32	70	166
T	Strained, aged	24·4	32·7	31	60–62	165
	Strained, aged, heated 1 hr 650°C.	24	32·4	30	60–62	171

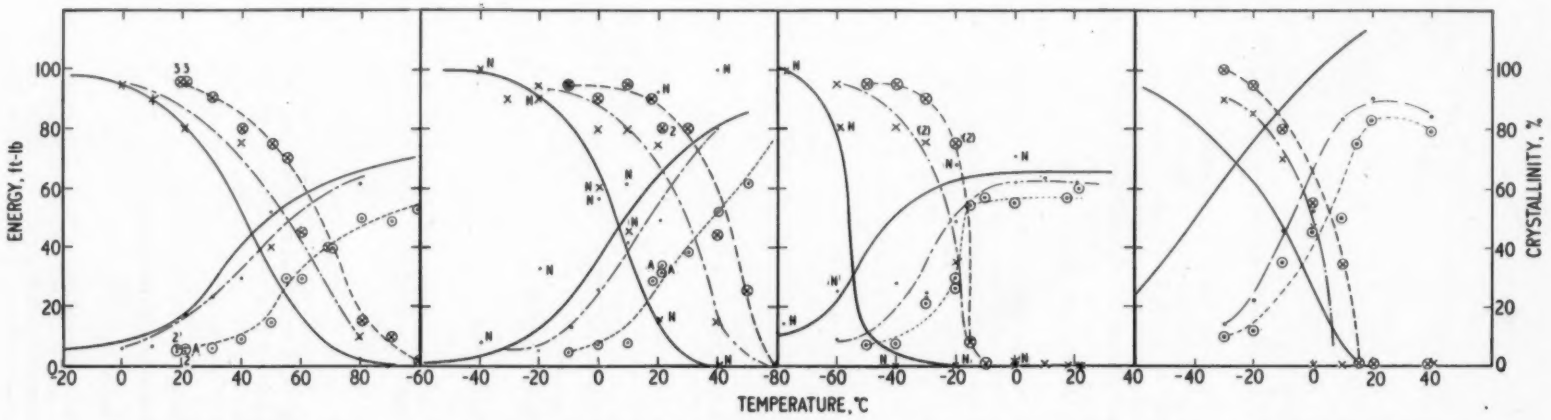


2—*Impact test results, steel* P

3—*Impact test results, steel* Q

4—*Impact test results, steel* T

5—*Impact test results, steel* R



6—*Impact test results, steel* S

7—*Impact test results, steel* P, *transverse*

8—*Impact test results, steel* Q, *transverse*

9—*Impact test results, steel* T, *transverse*

AACSS survey, mean curves
Strained, aged, energy
Strained, aged, crystallinity
A Specimens broken in Avery machine C.U
Strained, aged, heated, 650°C. energy
Strained, aged, heated, 650°C. crystallinity
N Strained, normalised 850°C.

assess because of changes of shape of the curves. These were accompanied by similar changes in the crystallinity curves.

The 650°C. treatment resulted in considerable recovery in all tests made in the direction of rolling and straining, but return to the original condition was not complete and was least in plate *T*. This plate was laminated and gave a great deal of scatter in all tests made, but the trend is clear. Normalising at 850°C. brought the four tests on plate *T* to values slightly exceeding those of the mean curve; the corresponding results for *Q* were better than those shown by the original figures. These results are in agreement with the fact that plate *T* was originally in the normalised condition, while *Q* was in the as-rolled condition.

Recovery in the transversely cut specimens was negligible except for *T*, and there was a slight shift towards lower temperatures shown by the crystallinity curve.

The tensile and hardness test results were in accordance with the impact tests, except for steel *T*. Straining and ageing raised the tensile strength and hardness and lowered ductility in all conditions investigated. Recovery after the 650°C. stress relieving treatment, however, was complete only in *T* in the lengthwise direction, although it was nearly so in the cross direction. It will also be noticed that the 650°C. treatment on the as-rolled material *P* produced less change, as compared with either *Q* or *T*. Stress relieving of the steels *P* and *Q* in the as-rolled condition was carried out on single specimens only, the effect being negligible although ductility was slightly impaired. The lengthwise direction samples showed considerable although incomplete recovery, and in the transverse direction samples there was a slight increase in tensile strength, associated in *Q* with decrease in ductility. The differences were so small in the transverse direction that they might be dismissed as the result of experimental and material scatter, were it not for the fact that all the changes were in the same direction in all materials.

Microstructure and X-ray investigation

Examination of the microstructures in the different conditions did not indicate that there had been any refining of the ferrite. There seemed to be a very slight change in the pearlite towards the development of a granular structure, but it was by no means complete.

Laue back-reflection photographs were made from the steels *P*, *Q*, and *T*, in the strained and aged condition and after heating at 650°C. Before examination, the specimens were electro-polished to a depth of 100μ to remove the surface deformation caused by metallurgical polishing.

A Hilger-Watts microfocus tube was operated at 25 kV using a focal spot size (foreshortened) of 80× 110μ giving a mean convergence of $1{\cdot}9\times10^{-3}$ radians at the surface of the specimen. The advantage of the microbeam technique is that reflections from fewer crystals are obtained and they do not so readily fall on top of one another and so mask the character of the reflections.

In the strained and aged condition, all three specimens *P*, *Q*, and *T* showed evidence of a rather ill-defined sub-grain structure. Annealing at 650°C. cleaned up this sub-structure, but the main effect was to cause recrystallisation of most of the material. The specimens in order of decreasing percentage recrystallised material were *T*, *Q*, and *P*. In this order the steels are of both increasing initial grain size and final recrystallised grain size.

The X-ray results are in full accordance with the changes in the mechanical properties. Although no visible changes in the ferrite were observed, almost complete recovery from work hardening was attained.

Conclusions

The general effects of plastic strain and the 650°C. anneal given to these materials are what would be expected. They show that strains of this magnitude are sufficient to raise the transition temperature of steels of several types, including those which were fully killed and normalised. A considerable degree of recovery is brought about by the 650°C. treatment. The directional properties may be due to a Bauschinger effect, although it is surprising to find that it persists into the plastic range to affect tensile strength, hardness, and ductility. Further work is required to investigate the matter fully.

Hardness surveys of welds made by Dr. Wells (Fig. 4, p. 270) for *P* and *Q* steels show values of 155–160 D.P.N. at 2 in. from the centre-line of the weld. These figures correspond with those given in Table II for the material in the strained and aged condition and having the raised transition temperature. This fact cannot be ignored in looking for an explanation of the development of cracks near welds. It points to the paramount importance of plastic strain.

Acknowledgments

This work has been carried out with the co-operation of Dr. Wells in connection with the survey of the five plates by the Admiralty Advisory Committee on Structural Steels.

The author wishes to acknowledge the co-operation of Mr. D. Warrington of the Crystallography Laboratory, Cavendish Laboratory, Cambridge, in making the X-ray investigation.

NEWS and Announcements

News of the Institute and Branches
B.W.R.A. · Other Societies ·
and Industry

INSTITUTE ACTIVITIES

MEETINGS

Aluminium

The Netherlands Welding Society and the Institute of Welding have organised a Joint Meeting on the Welding of Aluminium. It will be held in Utrecht from **Wednesday, 31st May to Friday, 2nd June 1961.**

The programme is as follows:

Wednesday, 31st May

Morning Session

10 a.m.—Opening by ir. W. P. Kerkhof, President of the Netherlands Welding Society.

10.15 a.m.–12.30 p.m.—Presentation and discussion of the papers on 'Weldability'.

"*Some remarks on weldability of aluminium*", by Prof. ir. G. Westendorp

"*Factors influencing the properties of welds in aluminium*", by J. C. Bailey, B.Sc., F.I.M. and G. W. Eldridge, A.I.M.

(*Chairman*: ir. W. P. Kerkhof)

Luncheon

Afternoon Session

2.0–4.0 p.m.—Presentation and discussion of papers on 'Construction'.

"*Some notes on the design of chemical equipment in aluminium*", by Prof. ir. F.C.A.A. van Berkel and Prof. ir. E. F. Boon

"*Some design considerations for welded aluminium*" by S. R. Banks, M.Eng., A.M.I.C.E., M.I.Struct.E., and R. E. Smith, M.A.

(*Chairman:* Mr. Edgar Fuchs, M.A., M.I.Mech.E., President of the Institute of Welding.)

5.30 p.m.—Reception at the Town Hall by the Mayor and Corporation of Utrecht.

Thursday, 1st June

Morning Session

10.0 a.m.–12.30 p.m.—Presentation and discussion of the papers on 'Welding'.

"*Aluminium welding practice*", by L. Capel

"*Development of Mig techniques for welding aluminium*", by D. Slater, B.Sc. and J. E. Tomlinson, B.Sc., A.M.I.

"*Recent specification for Class I pressure vessels of aluminium and aluminium alloys*", by F. Smith, D.F.C., B.Sc. (Eng.), M.E.T.

(*Chairman*: Prof. ir. C.A.A.v.d. Woude, Director, Netherlands Centre for Welding Technique.)

Luncheon

Afternoon Session

Visit to the Welding Exhibition "Lastu-61".

7.0 p.m. (approx.)—Informal dinner to which British guests are cordially invited.

Friday, 2nd June

Industrial Visits
(9.0 a.m.–6.0 p.m.)

(1) The Shell Refinery at Pernis (morning) and The Shipyard of Wilton-Fijenoord N.V. at Schiedam (afternoon). (Pernis-Schiedam by boat); or

(2) N. V. Philips Gloeilampenfabrieken, Eindhoven.
Demonstration of stereophonic sound and three-dimensional projection, visits to Light Laboratory and to industrial equipment and television factories;
or

(3) Werkspoor N.V., Amsterdam (morning) and Utrecht branch (afternoon).
Amsterdam: Manufacturing and assembly of all sizes of diesel engines. Under construction are engines in non-magnetic materials.
Utrecht: Visit to a newly built shop for fabrication of pressure vessels. Demonstration of aluminium welding.

The papers for discussion are published in this (May) issue of *BWJ* and in the April issue of *Lastechniek*.

The closing date for enrolment was 15th April.

Exhibition and Conversazione

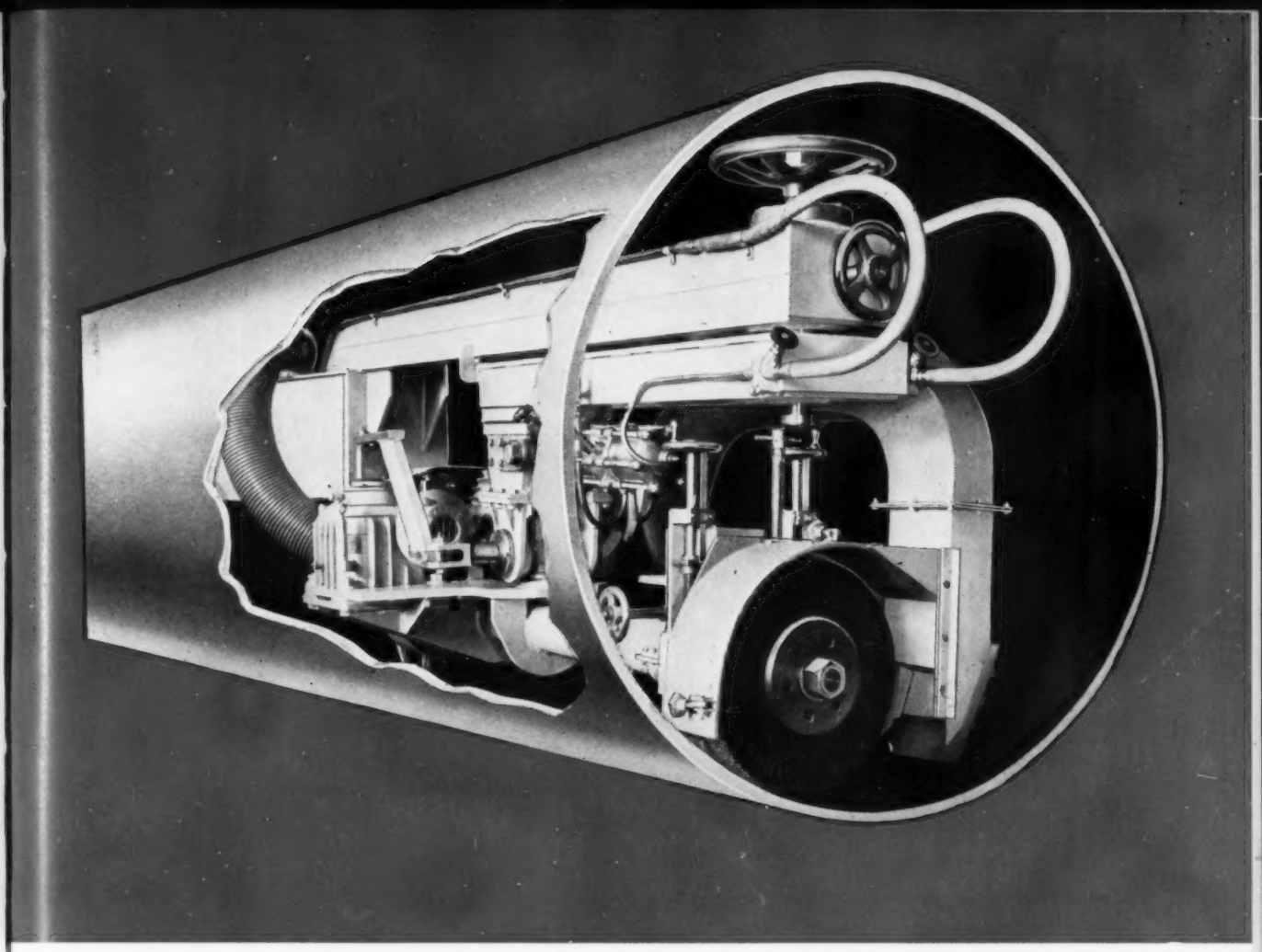
The South London Branch of the Institute of Welding is organising an Exhibition and Conversazione on Wednesday, 14th June, with the theme "*Quality control in welding*".

This will feature a display of failed welds, structures, and vessels in a range of thicknesses in mild steel, stainless steel, aluminium, and other alloys. The effect of defects on mechanical properties will be demonstrated in a special display, as will research into non-destructive testing methods.

The manufacturers of non-destructive testing equipment are co-operating in showing a comprehensive display of latest techniques including:

Ultrasonic examination of welds
Betatron and other modern radiographic techniques
Xero radiography
Fluorescent and dye penetrants
Magnetic crack detection
Leak testing.

Kindred organisations in the inspection and quality control fields are being invited to the meeting, which will be



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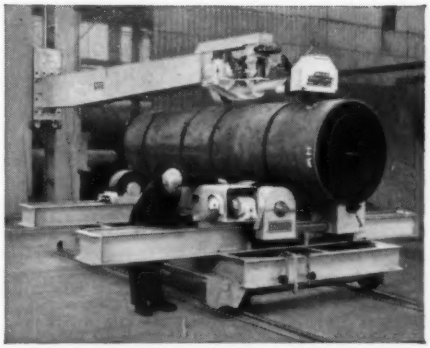

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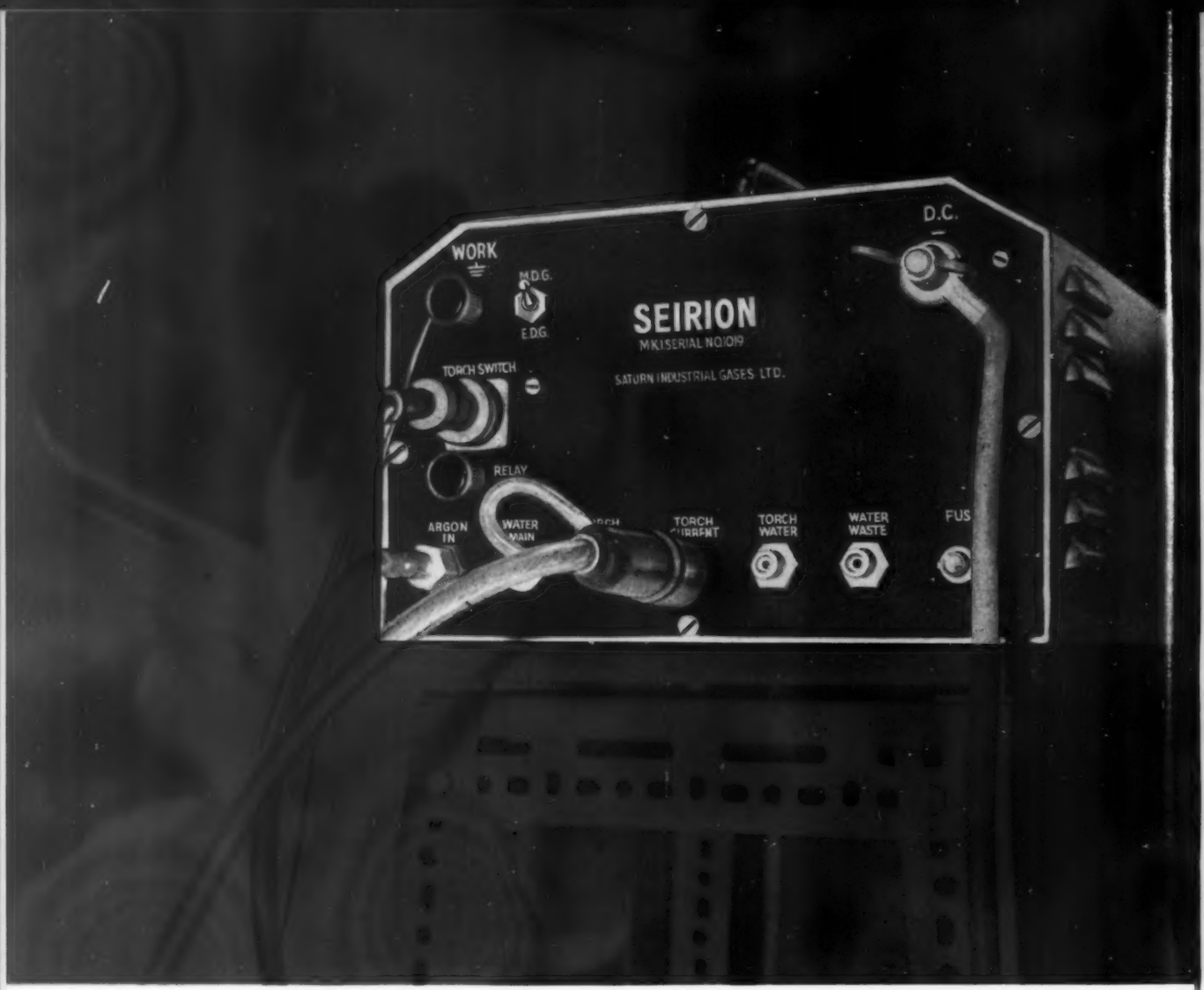

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similar to the successful 1959 Conversazione.

The exhibition will be open from 3 p.m. until 8.30 p.m., and tea will be provided on the terrace of the Institute during the afternoon and evening.

Further details are obtainable from the

Honorary Secretary
N. T. Burgess, Esq.
Central Electricity Generating Board
157 Blackfriars Road
London S.E.1

COUNCIL NOMINATIONS

The Council has unanimously agreed to the following nominations for the Council Elections of 1961.

President

Mr. H. West, M.Sc., M.I.Mech.E.

Vice-Presidents

Mr. C. H. Davy, M.I.Mech.E.
Mr. L. Redshaw, M.Eng., M.R.I.N.A.

Honorary Treasurer

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To represent Industrial Corporate Members

Mr. E. V. Beatson, B.Sc.(Eng.), M.I.E.E
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Mr. S. H. Griffiths, F.I.M.
Mr. T. McIver
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Mr. E. S. Waddington, F.S.E., A.M.S.A.I.Mech.E., Assoc.I.E.E., Assoc.S.A.I.E.E.
Mr. R. M. Watts, M.I.Mech.E.
Dr. R. Weck, M.I.C.E., M.I.Mech.E.

To represent Companions

Mr. J. Hooper

To represent Associates

Mr. A. Evitts
Mr. A. Miller

ELECTION OF MEMBERS

The following elections have been made, effective from 15th December, 1960.

Members

†E. J. French (Cambridge).

Associate Members

R. S. Belsten (Bristol); H. N. C. Bryan (Worcs); R. E. Dilks (Whitley Bay); D. Jones (Chester le Street); D. K. Roy (India).

Graduates

A. R. Bawden (Lincs); P. R. Hammond (London); A. E. Obasogie (Nigeria); J. E. Williams (Birmingham).

Associates

G. Bonson (Glasgow); J. M. Harper (Stockton on Tees).

The following elections have been made, effective from 26th January, 1961.

Members

*A. S. Bartlett (S. Wales); W. Bates (Manchester); T. M. Calvert (Herts); A. M. Carrick (Glasgow); T. S. MacNeish (London); L. M. Morley (Chesterfield); A. B. C. Rankin (Essex); *K. Ward (Essex).

Associate Members

T. L. Allen (Leics.); G. Brazendale (Warrington); W. J. Griffiths (Penketh Lancs.); ‡N. J. Hill (Cheshire); H. V. Huxley (Somerset); ‡M. J. Kaye (Banbury); J. H. Lane (Banbury); D. L. Matthews (Bath, Som.); C. J. E. Morris (Berkhamsted); F. B. Perry (Saltcoats, Ayres.); M. Saleh (Egypt); A. J. Smart (Bristol); D. C. Smith (Worcs.); L. West (Lincoln); N. T. Williams (Surrey); J. B. P. Williamson (Cambridge); B. F. Worrall (Warrington).

Companions

G. Betts (Wakefield); R. Moore (Worcs.); J. S. Owen (Cheshire); B. G. Reynolds (Essex); G. H. Richardson (Co. Durham); D. W. E. Stafferton (Sheffield).

Graduates

P. H. Baldwin (Walsall); B. Maynard (Middx.); G. A. Peacock (Swarkestone, Derbyshire).

Associates

J. Adam (Paisley); D. J. Barry (London); E. Cleary (Rotherham); H. E. C. Cleverley (Wiltshire); G. J. Davies (Glamorgan); R. Eacott (Staffs); J. M. Everett (Barrow in Furness); P. Gough (Castleford); D. V. Heydon (Swindon, Wilts.); K. L. Ho (Malaya); A. J. Hulme (Co. Durham); D. T. Parr (London); A. G. Rainey (Staffs); J. A. Skeate (Surrey); T. J. Sullivan (London); A. J. Udell (Swindon); G. Ward (Yorks); D. W. J. C. Young (Watford).

The following elections have been made, effective from 23rd February, 1961.

Members

A. W. F. Comley (Worcs.); E. G. West (Herts.)

Associate Members

J. G. Fowlie (Pembrokeshire); G. W. Ransome (Canada); E. Whaley (Co. Durham).

Companions

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Graduate

R. W. Hill (Middx.)

Associates

R. A. Cooke (Birmingham); T. H. W. Curtis (Windsor, Berks.); E.R. Dungar (Wolverhampton); J. McCulloch (Glasgow); B. Murray (Dublin); K. W. Peacock (Middx.); T. J. Willetts (Stourbridge).

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* Transfer from Associate Member.
† Transfer from Companion.
‡ Transfer from Associate.

Post-Graduate Course in Welding Technology

British Oxygen Welding Bursaries

In another part of this issue (p.258) we print the prospectus of the Post-Graduate Course in Welding Technology, which opens on 9th October, 1961, at the College of Aeronautics, Cranfield, Bletchley, Bucks., and closes on 6th July, 1962.

The British Oxygen Company have provided two bursaries of the value of £600 each, tenable in this course, and the Council of the Institute of Welding now invites applications for awards from suitably qualified persons.

Applicants should be graduates in engineering, naval architecture, or metallurgy of a British university or should hold equivalent educational qualifications. They should have experience in the practice or advanced teaching of engineering or metallurgy. They should be not more than 30 years of age on 1st October, 1961.

The tuition fees for the year's course are £75 and the residence charge, including full board during terms and the rent of an individual study bedroom, is £126 10*s*. 0*d*. These charges will be paid by the student out of the emoluments of the bursaries.

Selected students may spend the long vacation of 1962 in project work at the College.

Applications should be made by letter to the Secretary of the Institute of

Welding, 54 Princes Gate, Exhibition Road, London S.W.7, and should give: (1) date of birth, (2) nationality, (3) full particulars of general and technical education (schools, colleges, with dates, courses attended, examination results), (4) an account of industrial experience (names of employers, designation of posts held, nature of responsibility and dates), or of experience in teaching, (5) should name two persons willing to furnish confidential references, and should include (6) an undertaking to accept a bursary if awarded and to complete the course as a resident student at the College of Aeronautics.

The award will be made by the Council of the Institute of Welding, acting on the report of assessors, who will interview selected candidates in London between 12th and 16th June, 1961.

The closing date for the receipt of applications is **1st June, 1961.** Candidates who are invited for interview will be notified by 7th June. Awards will be announced on 14th July, 1961.

Swiss Association for Welding Technique

This Association, which was established in March 1911 as the "Swiss Acetylene Society", celebrated its Jubilee on 23rd and 24th March. The Association invited the Institute to send a representative, and Council requested the immediate Past-President, Mr. Seymour-Semper, to undertake this duty. Other countries who sent representatives included France, Germany, Belgium, Holland, and Sweden.

The Public Session commenced on 23rd March with a Beethoven symphony played by a very delightful quartet. Speeches were then made by Mr. G. Kaiser, President of the Swiss Association, two Government representatives, and Mr. P. Goldschmidt-Clermont, Past-President of the International Institute of Welding.

In the afternoon, visits were paid to local factories, followed by a Municipal Reception. A Banquet was held in the Casino de la Ville at which our representative, along with others, was able to offer good wishes on behalf of the Institute of Welding.

The following day was devoted to technical papers on various aspects of welding which in due course will be published in the official Journal of the Association.

NEWS OF MEMBERS

Obituary

The Council records with regret the death of the following member:

Mr. J. G. Williams (South Wales Branch, Hon. Member 1937). Mr. Williams was a Past-President of the Birmingham Branch.

With great regret we record the death, on 24th March, of **Lady Lillicrap,** wife of Sir Charles Lillicrap, K.C.B., M.B.E., President of the British Welding Research Association and a Past-President of the Institute of Welding.

Lady Lillicrap was a familiar and well loved figure at gatherings of the Association, and all members of the Institute and the British Welding Research Association will wish to offer their sympathy to Sir Charles.

CONTRIBUTORS TO THE JOURNAL

(*In April issue* BWJ)

Bernard Howard Baker, A.Inst.W., who is Senior Development Engineer, Semi-automatic Processes, at the Quasi-Arc Works of B.O.C., was born in London in 1924. He received a grammar school education at St. Ignatius College, Stamford Hill and at St. Chad's College, Wolverhampton, and studied part-time in welding and metallurgy at Birmingham and Wolverhampton Colleges of Technology.

Mr. Baker joined Quasi-Arc Ltd. (now B.O.C.) in 1940 and, apart from army service (mainly with the Royal Signals) from 1944 to 1947, has remained there since. His duties with the company are mainly with Technical Departments, and since 1953 he has concentrated extensively on semi-automatic bare wire processes.

N. Crevis, B.Sc., was born in 1931 and was educated at Raines Grammar School and at the Polytechnic, where he obtained an honours degree in Physics in 1951. On graduating, Mr. Crevis joined The British Oxygen group of Companies as a physicist, and has been concerned with research and development on arc welding.

F. W. Lunau, D.F.H., A.M.I.E.E., was born in 1922 and was educated at St. Paul's School and at Faraday House Engineering College. After wartime service in the Electrical Branch of the R.N.V.R. he was engaged firstly with the Gold Coast Government and then with Preece, Cardew & Rider, Consulting Engineers, on design and construction of power stations. In 1957 he joined British Oxygen Research and Development Ltd., now the Scientific Division of The British Oxygen Co., as a Senior Electrical Engineer, and has been largely engaged on research on bare wire gas-shielded welding.

Dr. N. Stephenson, formerly with the Ministry of Supply, National Gas Turbine Establishment, leads the Welding Section of the D. and R. Laboratories,

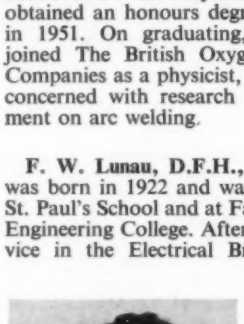
International Nickel Company (Mond) Limited, Birmingham. He graduated in Metallurgy from the University of Sheffield in 1945, and obtained his Ph.D. in 1947.

CONTRIBUTORS TO THE JOURNAL

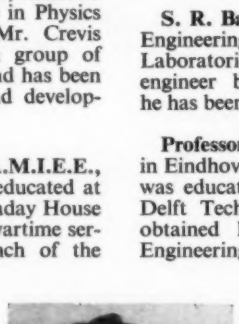
(*In this issue* BWJ)

S. R. Banks is Head of the General Engineering Division of Aluminium Laboratories Ltd., Banbury. A civil engineer by education and training, he has been at Banbury since 1947.

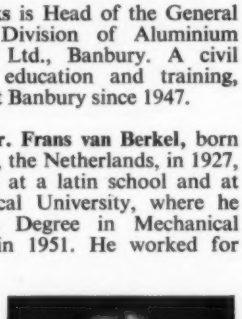
Professor Ir. Frans van Berkel, born in Eindhoven, the Netherlands, in 1927, was educated at a latin school and at Delft Technical University, where he obtained his Degree in Mechanical Engineering in 1951. He worked for



B. H. Baker



N. Crevis



F. W. Lunau

S. R. Banks

F. van Berkel

E. F. Boon

L. Capel

about seven years with the rayon and synthetic fibre concern Algemene Kunstzijde Unie N.V., at Arnhem, with the design and development departments.

In the following two years he acted as the project leader for the construction and starting up of the AKU/Goodrich synthetic rubber plant in Holland. Subsequently he was appointed a full Professor in Chemical Engineering at Delft Technical University.

Professor Ir. E. F. Boon is Professor Extraordinary in Nuclear Engineering at Delft Technical University. He was born in 1913, and at the age of 24 he took the Degree of Mechanical Engineering of Delft Technical University.

In 1938 he joined the Royal Dutch Shell Group as Mechanical and Chemical Engineer and remained with them until 1949. He then became full Professor in Chemical Engineering at the University and ten years later was appointed to his present position.

Since 1959 Professor Boon has also acted as Chief Engineer to the AKU group of companies; he is also advisor to the Netherlands Government on nuclear matters, and is a member of the Scientific Technical Advisory Committee of "Euratom".

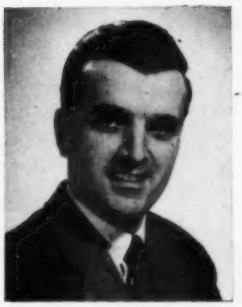
L. Capel is Chief Engineer of Werkspoor N.V., Utrecht, Netherlands.

F. Smith, D.F.C., B.Sc.Eng (Met.) is a Technical Officer on the staff of Imperial Chemical Industries Ltd., and deals with metallic and non-metallic materials of construction for chemical plant. He joined the Company in 1937, and after service in the Royal Air Force graduated externally from London University.

R. E. Smith, Head of the Structures Section of the Engineering Research Division of Aluminium Laboratories Ltd., Banbury, graduated in Mechanical Sciences from Cambridge University in 1948, and has since been employed in the Laboratories.

(It is regretted that the portrait of R. E. Smith was printed in the April News Section in place of that of R. S. Smith. Both portraits are now shown above.)

F. Smith



R. E. Smith

R. S. Smith

Dr. C. F. Tipper, M.A., Sc.D., D.Sc., (Constance Fligg Elam) was, until last year, Reader at the Cambridge University Engineering Department. She was educated at Newnham College, Cambridge, and worked at the Royal School of Mines under the late Sir Harold Carpenter and in Cambridge with Sir Geoffrey Taylor on the production and distortion of metal crystals.

She married G. H. Tipper of the Indian Geological Survey, and returned to Cambridge working in the Mineralogical and Engineering Departments, where, during 1939–1943, she lectured and ran the metallurgical laboratory.

In 1943 Dr. Tipper began work with Professor Baker for the Admiralty Ship Welding Committee, which continued until June 1960.

She was appointed Reader in the Engineering Department in 1949 until her resignation in June 1960.

BRANCH NEWS

East Midlands — Flame Cutting

On Wednesday, 18th January 1961, a paper was given at Loughborough College by Mr. K. D. S. Semper on "*Developments in flame cutting and flame planing*".

Mr. Semper opened his lecture by giving the history of oxy-acetylene cutting from the time it began, in about 1887, to its many present-day uses.

Cutting today is no longer a backyard job, and as accuracy is of utmost importance in industry, it is essential that all the equipment is maintained efficiently in order that improved output can be achieved: neglected equipment can cause a lot of trouble.

There was a lengthy discussion on the cutting of mild steel, the different methods that may be used when cutting stainless steel, plus the merits of introducing a powder or sand into the oxygen stream, and the use of a tungsten arc, shrouded by inert gas, in the cutting of aluminium.

In all cutting the economics of cost and speed have to be carefully considered, and the type of gas used plays an important part in the cost.

Mr. Semper spoke of the automatic machines that are made and stressed the importance, when three burners are being used, of the correct sequence of cutting in relation to each burner used: the methods of controlling distortion during multi-cutting operations were also mentioned.

Finally, Mr. Semper enlightened his audience on the theory of cutting by electronically controlled machines.

At question time he was kept very busy answering questions ranging from what process is best to use when cutting stainless steel to avoid contamination of the edges, to what is the thinnest material which can be cut satisfactorily. These were dealt with in a very satisfactory manner.

In a vote of thanks to Mr. Semper, Mr. Houghton said how grateful they were for this interesting paper, which covered such a broad field in the history of flame cutting.

H.S–C.

East of Scotland — Welding Advances

The fifth meeting of the 1960–1961 Session was held at 25 Charlotte Square, Edinburgh on Wednesday, 15th February 1961.

The meeting took the form of a lecture entitled "*Recent advances in electric welding*", given by D. B. Tait of B.O.C. Ltd.

The lecture was open to any interested persons, and it was well attended by members and friends.

The speaker covered aspects of the latest techniques in manual, semi-automatic and fully-automatic processes.

The talk commenced on semi-automatic argonarc welding, and some of the advantages mentioned were:

(1) Smaller and neater welds (down to $\frac{1}{32}$ in. for aluminium)
(2) Lower voltage and current (giving cheaper electricity accounts)
(3) Five times faster than gas welding
(4) Faster deposition (making gap filling easier)
(5) Twice as fast as manual welding with ordinary electrodes, with the added advantage that no de-slagging is required with argonarc.

The speaker touched on several methods of welding, which included submerged-arc and CO_2, but his main purpose was firstly a description of welding thin gauge metal, then in complete contrast the welding of metal 1 in. thick and over. Mr. Tait went on to describe the application of electro-slag welding.

The lecturer gave numerous sketches by way of explaining certain points, and a number of slides of diagrams and equipment were shown.

Of electro-slag welding it was mentioned that extensive research is at present going on in Britain and at the moment it has a limited application, but it is being used on a large scale in the Soviet Union. This type of welding gives good tensile and mechanical properties and low distortion, and good radiographs have been obtained.

A discussion followed the lecture, which brought out some interesting points, and was helpful to those present. The meeting concluded with a hearty vote of thanks, and the hope expressed that we would have a further visit by Mr. Tait in the not too distant future.

R.B.

Manchester — Electro-slag welding

For the 6th meeting of the session held on 1st February, Mr. A. M. Horsfield, M.A., A.I.M., talked to Branch members and guests on "*Electro-slag welding*".

Introducing the speaker, the Branch Chairman, Mr. E. H. Lee, said that Mr. Horsfield was probably the most knowledgeable person in the country on this subject at the present time.

Mr. Horsfield commenced by saying that the electro-slag process could be defined as the continuous melting and refining of a metal by feeding it into a high-temperature slag bath, the heat required being derived from the passage of an electrical current through the metal and the slag. The success of the process depends upon the fact that certain fluxes when fused become ionised, and are thus capable of conducting an electric current. The depth of the bath of fused flux can be adjusted so that the resistance between the tip of the metal being fed into the bath, and the fused metal beneath the flux will enable sufficient heat to be developed at a given current to melt the metal being fed into the fused flux at its feed rate.

The ability of the process to produce sound metal has led to its application in three important fields:

1. Welding industry
2. Foundry industry
3. Steelmaking industry.

The process was first introduced by the Russians about ten years ago and their object was to make possible the manufacture of large forgings and pressings, which were beyond the capacity of the Russian foundries at that time. The method used was to make the forgings in small manageable parts which were then joined together by electro-slag welding. It proved so successful that other applications were quickly found, and it has now become the preferred method of welding in the Soviet Union. It is the only fully automatic process which works in the vertical position, and the Russians now manipulate many of their jobs into this position, so that electro-slag welding can be used. Although the welding machines have been developed to a high degree of efficiency by continual modification over the past ten years, some of the original machines built by the Paton Institute in Kiev are still giving satisfactory service.

Mr. Horsfield went on to describe the process in much detail, saying that the temperature of the slag bath reaches 2400°C. and that water-cooled copper shoes are used to retain the molten metal and slag bath, and shape the weld bead. The water cooled shoes are connected to the carriage of the welding machine, which moves up the seam as welding proceeds. No special plate preparation is required other than square edges, flame cut or machined, and set up with a parallel vertical gap $\frac{3}{4}$–$1\frac{1}{2}$ in. wide according to the plate thickness.

Two types of machine are available, the larger to weld plates up to 20 in. thick using three electrode wires, and the smaller for plates up to 4 in. thick using one or two electrode wires. The process can be operated with either a.c. or d.c. power supplies.

Details were given of power source characteristics, fluxes and filler metals and the metallurgical aspect of the electro-slag welding process. Typical applications, such as thick walled pressure vessels, heavy press frames, turbine shafts, press cylinders, etc., were illustrated with slides and diagrams.

Some interesting questions were put to Mr. Horsfield at the conclusion of his lecture, and it was most unfortunate that some would-be questioners had to go unheard, due to lack of time. The vote of thanks to the speaker for a most interesting lecture was proposed by Mr. J. M. Whitworth.

A.C.M.

Sheffield — Transport Welding

A Joint Meeting was held with the Sheffield Branch of the Institution of Production Engineers on Monday, 12th December 1960. The lecturer on this occasion was Mr. G. Walton of the British Transport Commission, and his talk covered, in detail, the building of carriages and bogie frames by fabrication. The talk was very well supported by slides illustrating procedures adopted. Mr. Walton emphasised the need for paying special attention to tests of electrodes and to joint preparation.

During the discussion which followed, Mr. Earl asked if inspection during service was carried out and what form it took. A very detailed reply was given by the speaker, which left no doubt in the minds of all present as to the thoroughness of the British Transport Commission in these matters. The speaker was asked his opinion on cast steel bogie frames and fabricated ones: it was considered that fabricated frames were equally as efficient and probably the economics were in favour of fabrication.

Mr. J. A. McWilliam pointed out that stainless steel was used on the Continent, and the lecturer was asked why, in his opinion, this was not the practice in this country. The answer was that the cost could be three times that of mild steel and the weight saving and other economies would not be justified. The very lively discussion continued until closure.

A total of 57 members attended and it can be safely said that this Joint Meeting is becoming very popular.

South Western — Structural Welding

On Monday, 6th February, Mr. John S. Allen, A.M.I.C.E., M.Inst.W., of Horseley Bridge & Thomas Piggott Ltd., Tipton, presented a lecture entitled "*The use of welding in structural engineering*". The lecture held, by kind permission of

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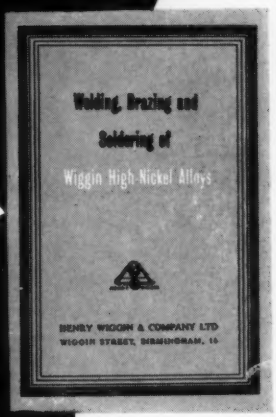

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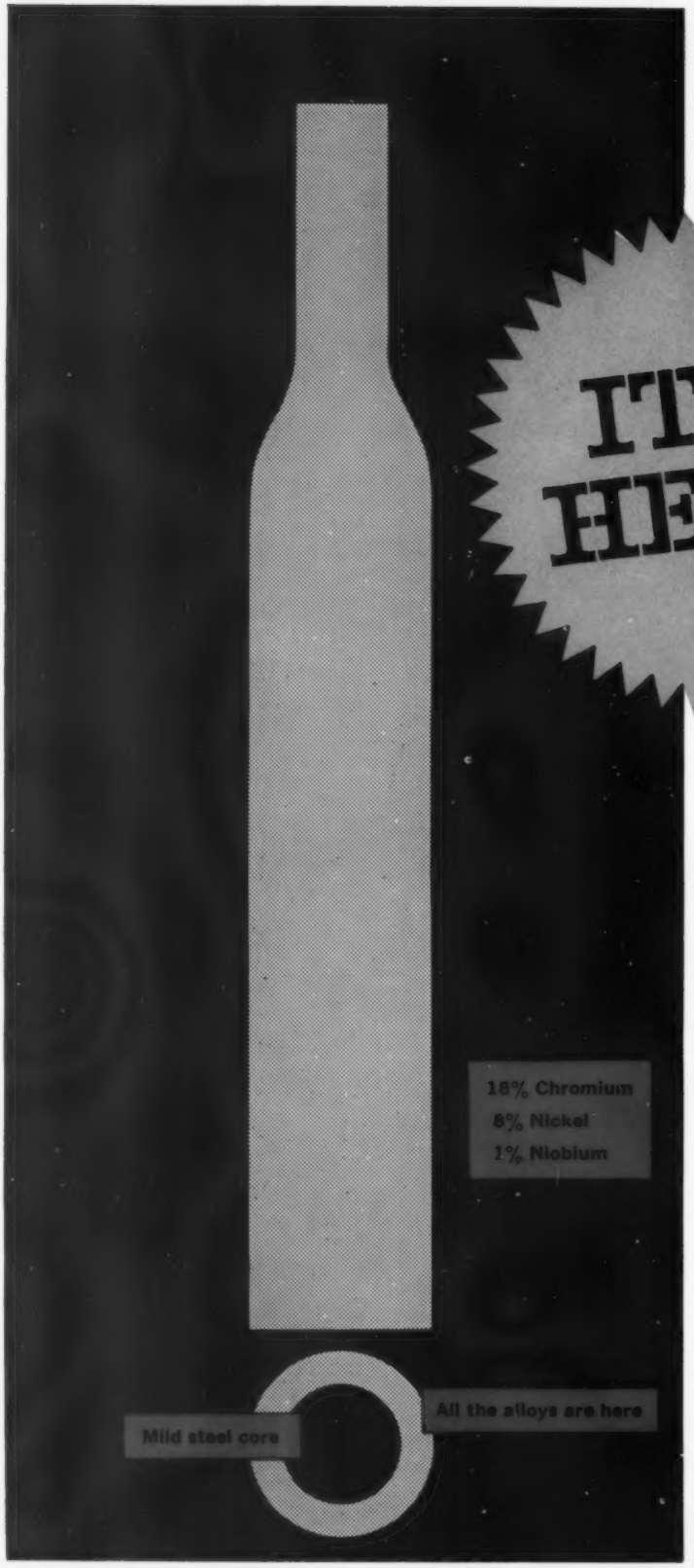

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the Directors of Messrs. Stothert & Pitt Ltd., Bath, in their New Canteen (extremely well appointed for such purposes) was a great success, and indeed this annual function may now be regarded as one of the highlights of the South Western Branch's programme.

Mr. Allen commenced his lecture by mentioning the advantages to be obtained in the use of welding in structural engineering and showed the savings when welding was applied to light structures, columns and struts, beams and beam connections, plate girders and rigid frames. He then considered the various aspects of the fabrication of the different types of unit and showed slides indicating the amounts of shrinkage to be expected from standard fillet and butt welds. From these figures it was possible to estimate the probable amount of overall contraction of any unit. Where welding is unbalanced about the neutral axes of the sections it is necessary to take special precautions to avoid unacceptable distortion. Methods of preloading and presetting were discussed and an example shown of the fabrication of I sections where three members were clamped together and by a suitable welding procedure four completed units were produced from two set-ups. Recommendations were given for the fabrication of girders and rigid frames and the advisability of completing the flange and web joints at the 'piece small' stage was stressed. Methods of correcting distortion by the application of heat from an oxy-acetylene torch were shown.

Mr. Allen then considered the application of welding to work on site and showed the many cases where it can be used to advantage. Careful forethought should be given to the fabrication of all welded work both in the shops and on site, and fabrication and welding procedures should be established for all important work. These procedures will enable the work to be properly controlled and will ensure that all steps possible have been taken to reduce distortion and minimise residual stresses. The procedures as initially conceived may well not be the most satisfactory, but they will have exercised a proper control and of course are capable of modification in the light of experience on the first members produced.

Completed girder being lifted into position. Girders were fabricated in three pieces, and straight-through site joints were welded after the pieces had been assembled on temporary staging

The speaker concluded by discussing the shop and site welding of heavy crane girders for a steelworks extension and of a number of high-tensile steel girders for a river bridge. Some coloured slides were shown of the work in progress on the bridge girders. The adoption of the recommendations made in the early part of the talk to these contracts enabled the work to be completed successfully.

During an interesting discussion, Mr. Allen dealt in detail with the positional butt welding technique developed for joining the pre-fabricated plate girders on site, mentioning the type of welding electrode used, sequence of weld runs, radiological examination of the completed joint and so on.

In proposing a vote of thanks Mr. G. Foster of Stothert & Pitt expressed appreciation to Mr. Allen for a first-class lecture and also commended him on his colour photography.

Mr. A. J. Francis, Branch President, thought that lectures of this nature would encourage young engineers to consider linking up with Institute of Welding membership, thus ensuring that they kept abreast with the latest welding developments which would be of considerable assistance to them in their careers.

E.M.W.

67 ton crane girder 107 ft long during trial assembly at the works. The flanges are 2¾ in. thick and the webs ⅞ in. thick, with 2 in. tongue plates

Wolverhampton **Bridge welding**

At the meeting of the Branch on 18th January there was once again 'standing room only' available—this time to hear a most interesting and well illustrated paper by Mr. J. S. Allen on "*Construction and Erection of Welded Structural Steelwork*" with particular reference to some recent high-tensile steel bridge girders.

Mr. Allen is well-known for the detailed investigations he has carried out in preparing suitable welding procedures for this type of work, and he opened his talk with a description of some of the more general fundamental principles. Probably the most important of these is the shrinkage and distortion which can occur during the welding of a large fabrication, and typical allowances are $\frac{1}{32}$ in. per 10 ft longitudinally and $\frac{1}{32}$–$\frac{1}{16}$ in. transversely. These values depend, of course, on the fit-up and the welding process used—the automatic, high-current processes tending to give rather less distortion. Mr. Allen emphasized that the designer could help considerably by keeping welding to the absolute minimum and ensuring that welding was balanced about the neutral axis as far as possible. Various methods of preventing 'unavoidable' distortion, such as on the flanges of long girders, were described, including a triple 'back-to-back' method in which four members were completed on a manipulator in only two settings.

In fabricating a girder it is preferable to build up flanges and webs to their full length before assembly as a girder, but in cases where this is impossible, such as on site, a very careful welding procedure had to be established. Usually this involved assembly with the gap between the web plates about $\frac{1}{16}$ in. greater than required. The flange welds are first partly (two-thirds) completed, then the web weld is carried out, backshipped and completed, and finally the flange welds are completed. The latter operation helps to relieve some of the locked-up stresses carried by the web weld.

Sometimes the procedure specified does not work out right first time, and correction of distortion becomes necessary. However, Mr. Allen emphasised that this was far preferable to allowing a random procedure, since suitable modifications can always be made in the light of experience.

The site construction of a high-tensile steel bridge presented some particularly interesting problems, not the least of which was salvaging the outboard motor of the personnel ferry—humorously described by Mr. Allen. Owing to the curvature of the lower flange it was undesirable to have machining allowances at the ends of each section of the girders, and weld shrinkages were therefore carefully pre-determined and suitable allowances were made. Preheating was avoided as far as possible by the choice of weld preparations which permitted the use of large electrodes. In some cases this involved the deposition of fillets of unequal leg-length, giving the equivalent strength of a smaller symmetrical weld.

Mr. Allen concluded his talk by showing some magnificent colour slides taken at various stages of construction and he and Mr. Flintham, who so kindly lent the Branch his projector, are to be congratulated on an excellent exhibition.

Mr. A. C. Clements opened the discussion with some pertinent points regarding distortion and shrinkage across heavy butt welds and Mr. Allen agreed that in some cases unequal double-V preparations were preferable. The use of firebuckets for preheating received caustic comment, but this was ably dealt with by the speaker who considered that their days were not yet numbered. Mr. Bennett regretted that so little use had been made of automatic welding in this field, particularly in view of the benefits which Mr. Allen had mentioned.

Mr. Allen was kept busy answering numerous other questions, and after Mr. Harper had proposed a hearty vote of thanks our Chairman reluctantly called another highly successful meeting to a close.

B.K.B.

EDUCATION

Post-Graduate Course in Structures and Materials

The 1961–62 post-graduate course in Theory of Structures and Strength of Materials will be held in the Department of Engineering, Cambridge University, beginning on 9th October 1961 and finishing in June 1962.

The latest advances made in the understanding of the behaviour of metallic structures under static, repeated, or fatigue loading will be the principal subject of the course, with particular emphasis on welding as a method of fabrication. No attempt will be made to teach conventional methods of design, but present-day practice and possible future developments will form the subject of critical study.

The object of the course is not to train research workers, but to help engineers to apply the latest advances in knowledge. The course will include lectures, colloquia and laboratory work, and each student will be encouraged to make a detailed study of some problem of particular interest to him.

The course is open to university graduates with industrial experience, and to others with suitable equivalent qualifications and of sufficient experience to obtain full benefit from a post-graduate course.

Further details and forms of application for admission may be obtained from the Secretary, Cambridge University Engineering Laboratory, Trumpington Street, Cambridge. The completed forms of application should be returned to the Secretary not later than **31st May 1961.**

NEW PLANT AND EQUIPMENT

Voltage surge detector

Portable Welders, Ltd. Buckingham, have introduced a transient voltage surge detector, which enables the actual surge to be seen on a c.r.o. as a fixed image. Suitable values of capacitance and resistance can then be brought into the circuit to suppress or greatly reduce the surge.

Argonarc torches

The full range of Tec Torch Co. (U.S.A.) products is now being marketed in Britain by Interlas Ltd. The range includes air- and water-cooled

argonarc torches in both pencil and angled types for manual welding, machine torches for automatic welding, and argonarc spot welding guns with control units.

The torches are very light, and are fitted with transparent nozzles to provide unrestricted visibility.

If needed, Miller power sources can be provided for use with this equipment.

Aluminium stud welding

Developments in aluminium stud welding were described by D. J. N. Laurie in the April issue of *BWJ* (p.116). By adding an argon shroud attachment and a preheat arc unit to standard equipment, Crompton Parkinson (Stud Welding) Ltd. claim to have reduced considerably the effects of porosity and oxidation in normally made stud welds. Successful welds have been made in the complete range of aluminium alloy studs up to $\frac{7}{16}$ in. dia.

STUB ENDS

▶Mr. John Roberts has been appointed Midland Area Representative for Weldcraft Ltd., Slough (one of the G. D. Peters Group).

▶Messrs. K. A. Ballard Ltd., of Worcester Park, Surrey, have been appointed London Agents to the Clyde Structural Iron Co. Ltd.

▶Mr. A. M. Browne, Chairman and Managing Director of Hackbridge and Hewittic Electric Co. Ltd., has been elected President of the British Electrical and Allied Manufacturers' Association. Mr. H. H. Mullens, Chairman and Managing Director of A. Reyrolle & Co. Ltd., has been elected Deputy President.

▶Details of a wider range of rough-machined seam-welding wheel blanks in Mallory 3 are given in Leaflet 7200/3 published by Johnson, Matthey & Co. Ltd. The blanks are now obtainable in metric sizes.

DIARY

8th–11th May—Industrial Finishes Exhibition and Convention (Earls Court, London)

8th–18th May—Mechanical Handling Exhibition (Earls Court, London)

31st May–2nd June—Institute of Welding—Joint Meeting with the Netherlands Welding Society in Utrecht. "*Aluminium*"

Current WELDING LITERATURE

Book Reviews
Additions to the Institute Library
Trade Publications

CONTENTS OF PERIODICALS RECEIVED

This section is intended to give a survey of the current welding literature received by the Institute of Welding Library. The contents lists are not exhaustive; only the main articles in welding journals are listed, and reprints from other journals and short notes are generally excluded. In addition, welding articles from other periodicals are listed. Abstracts of welding literature are given in the Bibliographical Bulletin of Welding and Allied Processes, *published by the International Institute of Welding, and details of this may be obtained from the Secretary of the Institute of Welding.*

Welding Journals

Canadian Welder, 1961, vol. 52, January

Welding at Chalk River, J. V. Cornwell (12–13)
Welded aluminium watercraft, H. Peacor (22)

Journal of the Japan Welding Society, 1960, vol. 29, November

Selection of welding conditions for CO_2 or CO_2–O_2 arc welding, I. Masumoto (3–15)
Effect of material and welding on the pull-out type fracture in fillet-welded joints. M. Watanabe and others (16–24)
Welding of cast iron and nodular graphite cast steels. Report 2, M. Homma and others (25–29)
Studies on porosity in welded joints. Report 2, Y. Ando and others (30–33)
Some basic experiments with acetylene purifier, I. Ueda and H. Sinotani (35–38)
A study of weld cracking in austenitic stainless steel. Report 2, H. Suzuki and others (39–44)

Journal of the Japan Welding Society, 1960, vol. 29, December

The urgent problem of welding education in the Technical High School, M. Okada and T. Ogita (3–9)
A study of weld cracking in aluminium and its alloys, H. Kihara and others (10–17)
Effect of alloying elements on notch toughness of basic weld metals. Report 5. Effect of phosphorus, H. Sakaki (18–23)
Hot ductility of stainless steels during weld thermal cycle. Report 2. Investigation of AISI type 347, 304 and 304L alloys, H. Suzuki and others (24–33)
On the porosity of weld metal deposited by gas-shielded metal-arc welding. Report 2. Effect of hydrogen, I. Masumoto (34–40)

Schweisstechnik (Berlin), 1961, vol. 11, January

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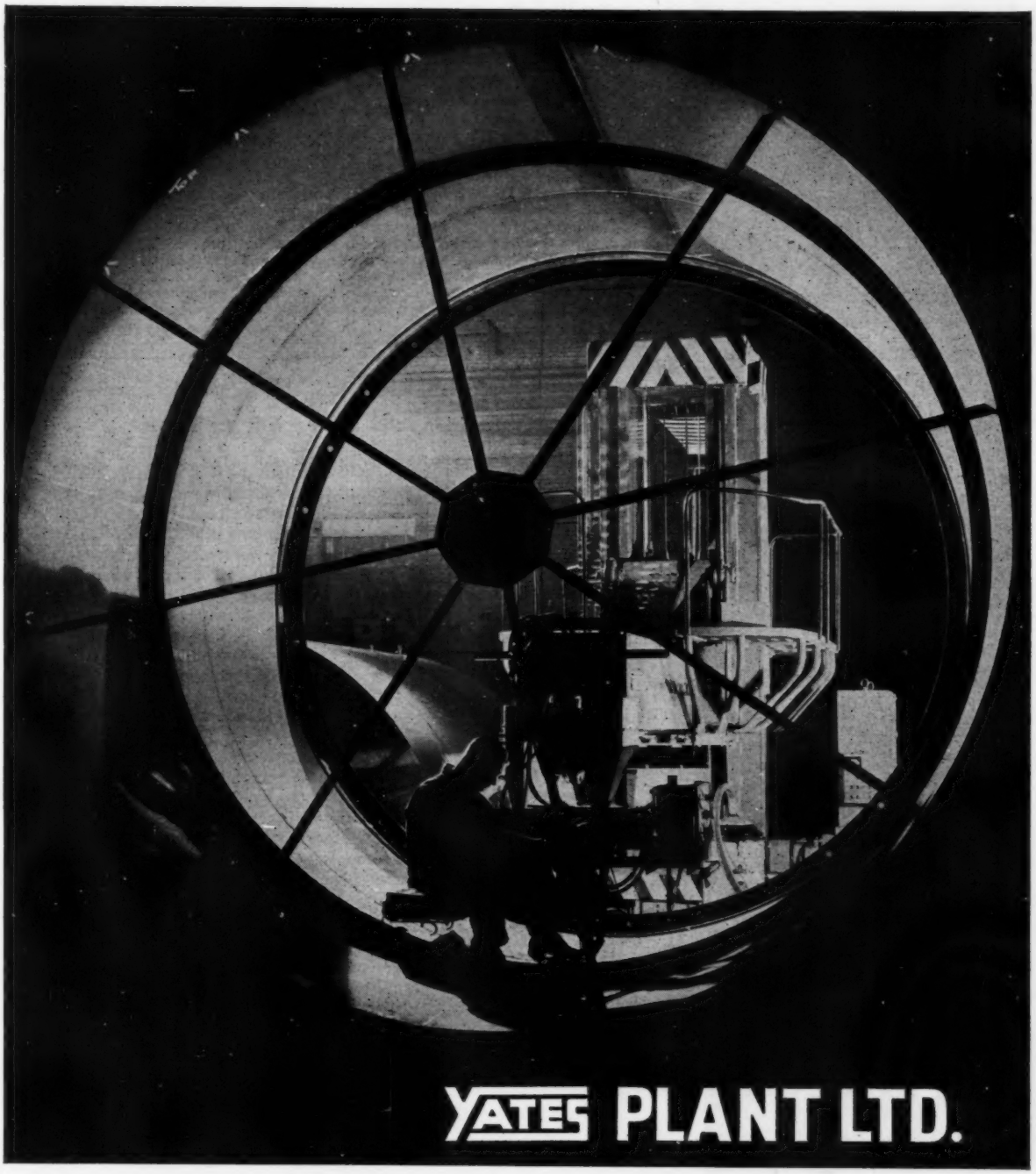

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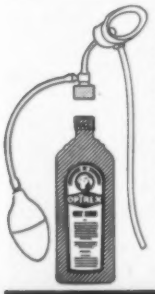

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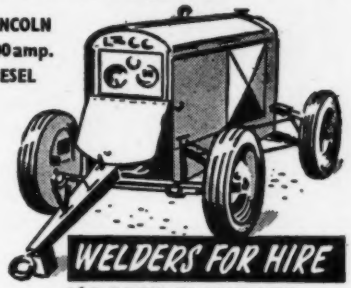

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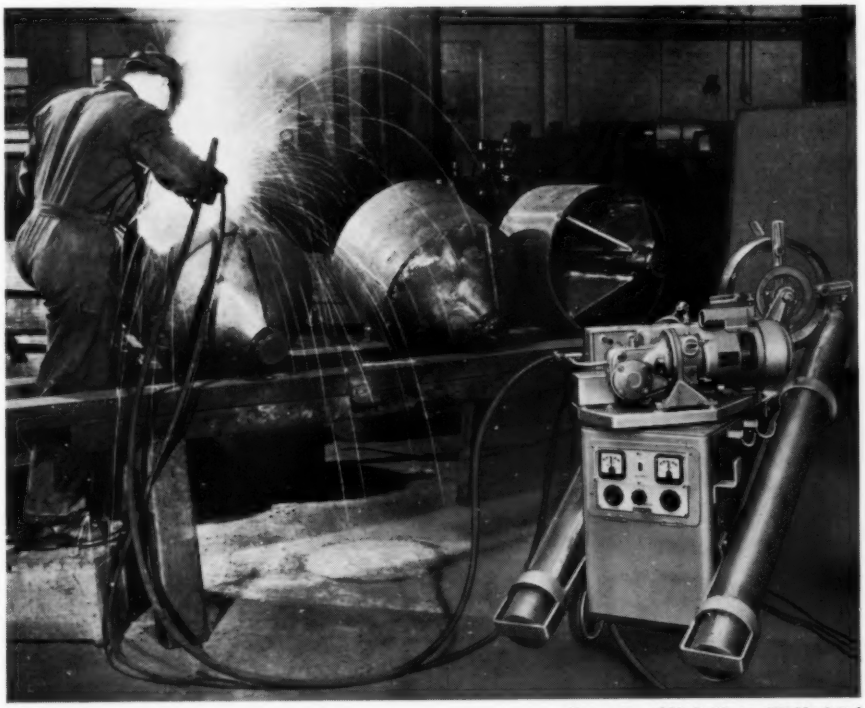

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